Laboratory and Finite Element Analysis study of potential factors involved in the failure of proximal resin composite sandwich restorations

By

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The candidate confirms that the work submitted is his/her own and that appropriate credit has been given where reference has been made to the work of others.

Dedication

I dedicate my dissertation work with a special feeling of gratitude to my loving parents (my Dad.Prof. Abdussalam Edwebi and my Mum Mrs.Kadeja Mansour), whose words of encouragement always empower me.

I also dedicate this work to my family especially; my husband (Dr.Tarek Almasri), who always encourage, support and help, and my lovely children (Taha, Ayah, Alla and Abdulraouf); who are the pride and joy of my life. I love you more than anything and I appreciate all your patience and support

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Abstract

Sandwich restoration technique was one of the proposed procedures with the intention of improving marginal integrity of direct resin composite restorations, especially when the cervical margin is situated below the cemento-enamel junction. Co curing, which defined as the simultaneous photo polymerization of two different light activated restorative materials, claimed to decrease the internal stresses in resin composite sandwich restorations. The aim of this research project was to investigate the cause of failure with this type of restoration. This research included two approaches; experimental and numerical analysis. The experimental part included three experiments; **(1)** the main study which included 104 proximal RMGIC/RC sandwich restorations in premolar teeth using Fuji II and Herculite, to investigate the effect of the co-curing technique in comparison to separate curing on the presence of microleakage. Two further studies were undertaking using Typodont premolar teeth. **(2)**The first one was to investigate the effect of tooth angulation on the adhesive thickness. **(3)**The second one was to assess the effect of the application technique on the adhesive thickness **Experimentally**, it was found that: 1. there was no difference in microleakage between the two curing protocols, 2. the thickness of the adhesive layer was far thicker than the manufacturer's recommendations of 10 microns, 3. angulation of the tooth during adhesive application may have an effect on adhesive pooling and lead to a thick adhesive layer, 4. adhesive application is a sensitive multi-stage procedure and further work may be needed to develop a consistently thin adhesive layer. The numerical approach was a Finite Element Analysis, **1**. to investigate the stresses distribution in the sandwich restoration.**2**. to investigate

the effect of a thick adhesive layer on stresses distribution. **The FEA results** revealed that, **1**. the stresses generated in the sandwich restoration were within the limits for tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II and Herculite materials; **2.** the addition of each new layer can relieve (reduce) the magnitude of the stresses induced by the curing of the previous layer, **3**. polymerisation shrinkage of the thick adhesive layer generated high stresses at the tooth restoration interface. **Conclusion:** Polymerisation shrinkage of the thick adhesive layer was responsible for the marginal failure of the sandwich restoration.

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Introduction

1.1 Introduction

This chapter provides the reader with an overview of this thesis. It introduces the aims and objectives of the study. A framework for the dissertation is provided at the end of this chapter. This research study is a collaborative work between School of dentistry and School of Mechanical Engineering in the Faculty of Engineering at the University of Leeds.

The integrity and durability of the margins of resin composite restorations is fundamental to the prevention or minimization of microleakage. This important interface has been a key focal point for research (Dietrich et al., 2000; Al-Saleh et al., 2010; Rodrigues Junior et al., 2010; Kasraei et al., 2011; Khoroushi et al., 2012; Hafer et al., 2013). The sandwich restoration technique was one of the procedures investigated with the intention of improving marginal integrity of direct resin composite restorations, especially when the cervical margin was situated below the cemento-enamel junction (McLean et al., 1985; Welbury and Murray, 1990).

Conclusive clinical evidence for the efficacy of the sandwich technique to restore proximal posterior preparations is still lacking (van Dijken, 1994; Lindberg et al., 2000; Lindberg et al., 2007). Co- curing has been proposed as a

solution to reduce gap formation and was found to eliminate the internal stresses within the restoration and minimize marginal leakage (Knight et al., 2006).

1.2 Aim:

The aim of this research was initially to examine the marginal leakage of proximal resin composite open sandwich restorations using Resin modified glass ionomer Cement (RMGIC) to investigate the effect of curing the two materials together or separately.

1.3 Objectives

1.3.1 Dye penetration test

To assess the dye penetration at the tooth /restoration interface using sectioning technique and Micro-Computed Tomography (Micro CT).

1.3.2. Finite Element Analysis

To analyse the stresses generated with sandwich restoration in order to detect the areas of high stress, which could be more susceptible to gap formation and microleakage.

1.4 The framework of the thesis

This research project is a combination of a laboratory and a numerical (FEA) study. The main laboratory experiment was conducted to investigate the effect

of a co-curing protocol on microleakage of RMGIC/RC restorations. The FEA was established to investigate stress distribution in the sandwich restoration. The result of these early studies led the investigator to follow an alternative investigation which then changed the initial aim from the investigation of the co-curing protocol to investigating the causes of marginal failure of adhesive restorations. Two pilot experimental studies were then carried out in order to assess the effect of tooth angulation and application techniques on the adhesive thickness. Another FEA study was conducted to assess the effect of the unexpectedly thick adhesive layer on the stress distribution.

The manuscript of this thesis is divided into ten chapters as follows:

Aim, objectives, and the layout of the thesis were covered in Chapter One.

Chapter Two is a literature review that presents the historical background of resin composite restorations and previous research in relation to microleakage in posterior resin composite sandwich restorations. The literatures on the factors which could lead to microleakage, as well as suggested solutions to the problem, were also presented. It also covers different methods of investigation used in vitro to assess microleakage. The chapter presents the use of finite element analysis in dental research and reviews previous research using finite element analysis.

The preparation for the laboratory part of the study which includes sample size calculation, sample collection, ethical approval application, selection and storage media for the sample were covered in **Chapter Three**.

Chapter Four includes the preliminary investigation of the study protocol on a small number of teeth to identify any deficiencies in the study design before undertaking the main laboratory study. This chapter details the materials and instruments used during placement of the restorations. The preliminary results, modifications to the study design, the conclusion and limitations of the study were also presented.

Chapter Five presents the main study which investigates the effect of the curing protocol on microleakage of RMGIC/RC sandwich restorations. In this chapter modifications to the study protocol were outlined. The aim and objective and the methodology were presented. The results were then discussed. These results led the investigator to alter the aim of the study from investigation of the effect of the curing protocol to investigating the reasons for adhesive restoration failure. The adhesive thickness was measured and result was then analysed and discussed.

Chapter Six includes two pilot studies to investigate the cause of a thick adhesive layer found in chapter 5. The first experiment was to investigate the effect of tooth angulation on the adhesive thickness. The second experiment was to determine operator compliance with the manufacturer's application instructions and to investigate the effect of any deviation from these instructions

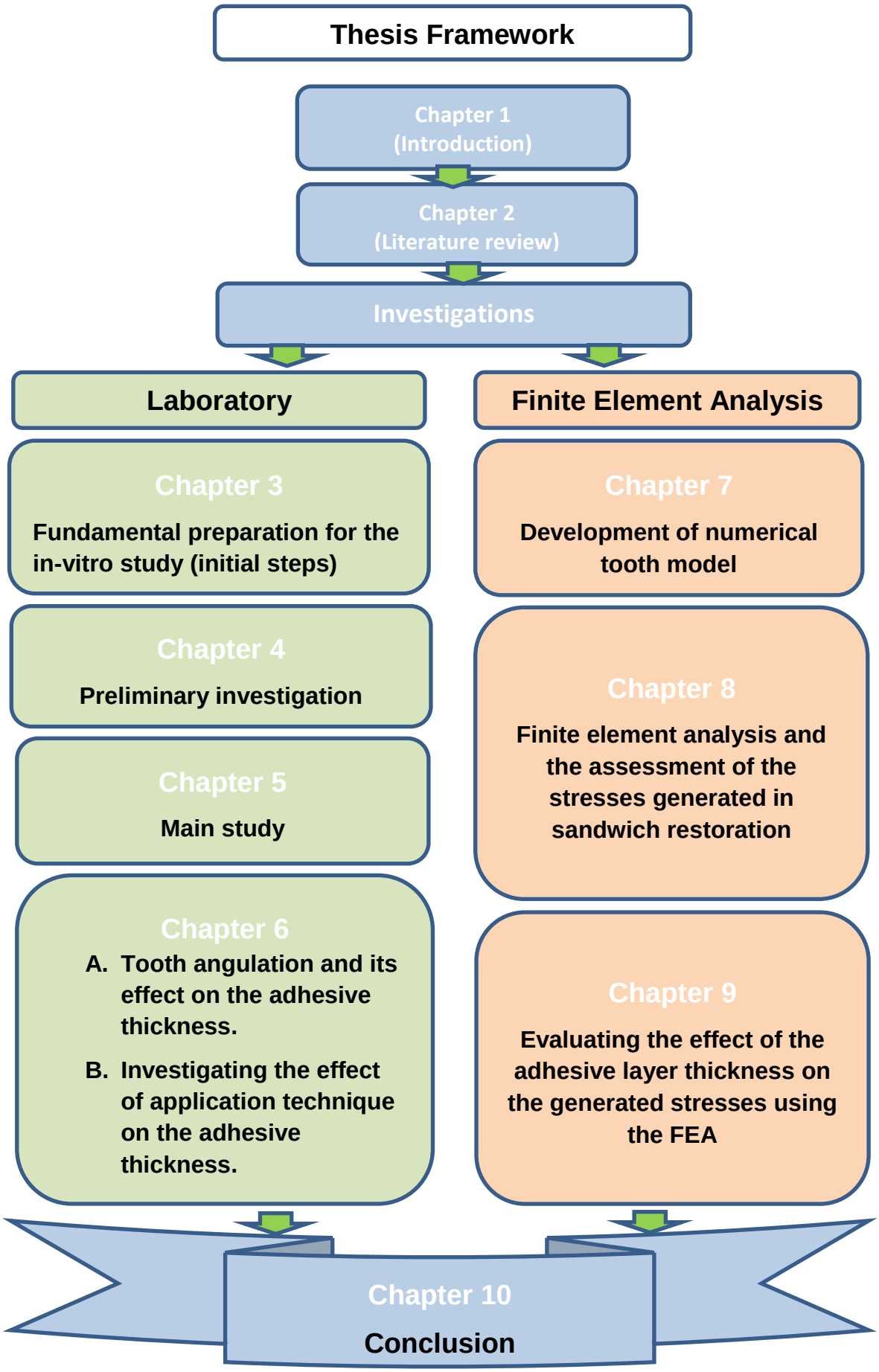
or inconsistencies in technique on the thickness of the adhesive layer. The chapter includes materials and methods used in the investigations. The result, discussions and conclusions were presented at the end of the chapter.

To begin the finite element analysis, some preparation was required**. Chapter Seven** covers the preparation undertaken which included the gathering of the material properties for the restorative materials and tooth structure from previous research. The development of a numerical model was undertaken, starting with the preliminary model, leading then to the generation of the idealised model using the details of the restoration and the tooth outline from the experimental tooth section.

Assessment of the stress generated in the sandwich restoration using FEA was presented in **Chapter Eight**. This included the steps followed to simulate the volumetric shrinkage of the applied materials (Fuji II, Herculite) and the determination of the temperature required to simulate shrinkage. The final part of the chapter presents the results, discussion and conclusion.

The aim of **Chapter Nine** was to investigate the effect of the adhesive layer thickness on the generated stresses using FEA. It includes the methods of calculating the volumetric shrinkage of the adhesive material used in the study and the determination of the temperature required to simulate area shrinkage. The result, discussion and conclusion were then presented.

Finally, the achievements of this dissertation and the overall conclusions were presented in **Chapter Ten**. The limitations and suggestions for future work were also outlined.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Chapter 2
Literature review

2.1 Historical background of resin composite restoration

Resin composites are the most widely used direct aesthetic tooth-coloured restorative materials. They were introduced in the 1960s, and were initially recommended only for the restoration of anterior teeth because of their poor wear resistance (Abell et al., 1983).The development of new formulations and more advanced technology for both the polymerization and application of resin composite materials has led to significant progress in their clinical performance and predictability and expanded potential uses (Leinfelder, 1997; Jackson and Morgan, 2000; Braga et al., 2005).

Traditional posterior resin composites had been shown to be inappropriate as filling materials for posterior teeth due to lack of condensability and packability. They also exhibited significant polymerisation shrinkage and showed poor wear resistance (Vanherle and Smith, 1985). At this point, amalgam was the most widely used material for occlusal and proximal restorations because of its high strength; good wear resistance, technique insensitivity, low cost and adaptability for restoring small, medium and large lesions with an estimated success rate of about 87% after 6 years (Roulet, 1997).

During the late eighties, the physical and mechanical properties of resin composites were improved significantly to suit the requirement of posterior restorations. Patients have become more attracted to the idea of “white fillings” and increasingly request a restoration that matches the colour of their natural teeth. They are, despite the lack of scientific evidence, increasingly concerned about the hazards of using mercury containing materials and health implications (Widstrom et al., 1992; Tyas, 1994). That has led to resin composite becoming the most widely placed direct restoration alternative to dental amalgam (Jordan and Suzuki, 1991; Walmsley, 2002; Lyons, 2003).

Alongside, a significant decline in the acceptance of amalgam has been reported because of the problems encountered with the corroision of amalgam and the difficulty in bonding to tooth structure with the need to sacrifice sound tooth structure to gain retention (Jokstad and Mjor, 1991). These, in addition to aesthetic concerns and the continuing debate about potential mercury toxicity, have led to a decline in the use of amalgam (Lutz et al., 1996).

Amalgam, compared with resin composite, requires undercuts, pits or grooves to provide mechanical retention, which can be at the expense of healthy tooth structure. In contrast resin composite requires minimal tooth preparation, and provides more aesthetic results (Bedran-Russo and Swift, 2007). Welbury et al (1990) reported that the surface occupied by the restoration was larger with amalgam than when resin composite was placed for an equivalent lesion size, which confirms that amalgam is necessarily more destructive.

Since its inception, resin composite materials have improved substantially by the introduction of new formulations and the development of dentine adhesive systems (Kugel and Ferrari, 2000; Hervas-Garcia et al., 2006). They remain, however, technique-sensitive, difficult to place and their long term performance is still compromised by polymerization shrinkage stress (Yoshikawa et al., 2001). The generated stress can result in the development of micro-crack propagation (Kanca and Suh, 1999; Jorgensen et al., 1975); cuspal movement (Suliman et al., 1994; Alomari et al., 2001) inadequate marginal seal and gap formation that consequently leads to microleakage (Campos et al., 2005).

2.2 Microleakage

Microleakage is defined as “the clinically undetectable passage of bacteria, fluids, molecules or ions between a cavity wall and the restorative material applied to it” (Kidd, 1976). A considerable number of researchers identified this phenomenon and reported its association with post-restoration hypersensitivity, discoloration at restoration margins, recurrent caries, pulp inflammation and / or decisive failure of restorations (Pashley, 1990; Cox, 1994; Sasafuchi et al., 1999; Fleming et al., 2005; Arora et al., 2012) (Figure 2.1).

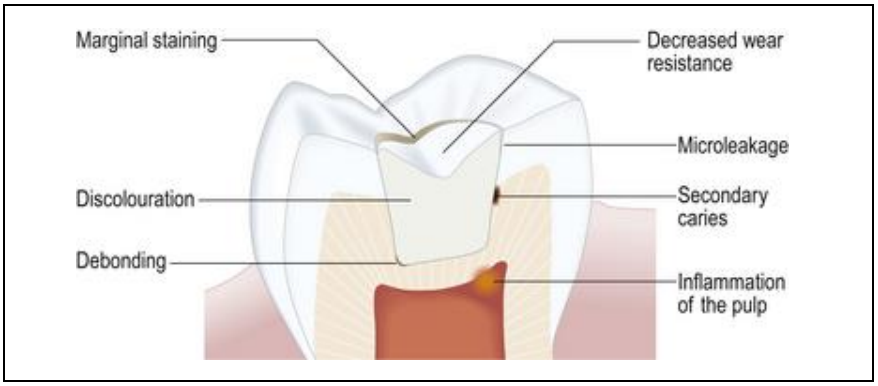


Figure 2.1: Microleakage and its consequence on tooth restoration.

Image source: http://pocketdentistry.com/7-the-tooth-coloured-restorative-materials-i-resin-composites/

Consequently resin composite materials continue to attract much laboratory and clinical research with the purpose of improving handling characteristics, curing methods and compensating for polymerization shrinkage (Deliperi and Bardwell, 2002; Ritter, 2005; Idriss et al., 2007; Majeed et al., 2009) aiming to attain perfect and complete seal of the restoration's margin, which in turn may help to prevent or eliminate microleakage.

The integrity and durability of the restoration margins to prevent or at least minimize microleakage constitutes a key focal point for researchers (Dietrich et al., 2000b; Rodrigues Junior et al., 2010). Therefore microleakage studies using dye penetration methods are still the most common and simplest approach in dental research in terms of obtaining information about the quality and behaviour of dental restorations (Fabianelli et al., 2010; Roberts, 2011; Moazzami et al., 2014; Parolia et al., 2014).

2.3 Factors influencing microleakage

Microleakage can be related to a number of factors, such as dimensional changes of the material due to polymerization shrinkage, thermal contraction and mechanical stress (Staninec et al., 1986). Several other factors can indirectly contribute to microleakage of resin composite restorations such as the curing variables; application techniques; geometry of the preparation and position of preparation margin (Braga and Ferracane, 2004; Alomari et al., 2007).

2.3.1 Polymerization shrinkage of resin composite restorative materials

Polymerization shrinkage is one of the main concerns for dental practitioners when using resin composite materials. It can be defined as volumetric reduction of the bulk of the composite during the conversion of monomer molecules into the polymer network (Venhoven et al., 1993; Davidson and Feilzer, 1997; Davidson and Davidson-Kaban, 1998). This conversion can set up stresses which could increase contractile forces and bulk contraction of the materials with consequent reduction in volume. This process sequentially generates a gap between the resin composite and the tooth structure and consequently allows microleakage (Haller and Trojanski, 1998). The stress could potentially initiate adhesive failure in the composite/ tooth interface if the contraction stress exceeds the dentine bond strength (Davidson et al., 1984). On the other hand, if the bond to the tooth structure is strong enough, tooth structure will be exposed to a stress and potential fracture (Alomari et al., 2007).

2.3.2 Curing light variables

The effect of curing light and its related variables on microleakage of resin based restorations has been well documented in the literature (Shortall and Harrington, 1996; Danesh et al., 2004; Strydom, 2005).

Those variables can be divided into:

1. Curing equipment related factors such as bulb frosting or degradation, light reflector degradation, light tip contamination, light intensity and wave length.

2. Procedure related factors including light tip direction, access to restoration surface, distance from surface and time of exposure.

3. Restoration factors such as restoration thickness, cavity design, filler content and size and restoration shade.

All of the above mentioned factors have an effect on the polymerization of resin composite restorations (Roberson et al., 2006; Strydom, 2002a; Strydom, 2002b).

Several sources of curing light for resin based materials are available. These include; halogen lamps, plasma arc lamps, laser and light-emitting diode (LED) lights. The conventional curing light (halogen lamp), however, showed better results than using the plasma arc curing light and was comparable to the soft start curing protocol (Cavalcante et al., 2003; Danesh et al., 2004). Fleming et al. (2007), has reported that using a light-emitting diode (LED) light curing unit significantly increased the microleakage scores. The LED light has shown to be less efficient in curing the resin composite in comparison with the halogen light

which was shown to deliver greater total energy and produced a hardest resin composite (Price et al., 2003).

The intensity of the curing light has been considered as the main factor which can considerably affect the degree of polymerisation, and the depth of curing of resin composites. A reduction in light intensity as stated by Shortall and Harrington (1996) can lead to:

- A decrease in curing depth which results in a lower surface microhardness which also affects the integrity of the restorative interface with the preparation walls.
- An increase in the incidence of restorative margin fracture.
- Enamel margin fracture and marginal openings.
- Increased shrinkage stresses, which probably results in significant interfacial leakage and early failure of the restoration (Feilzer et al., 1995; Dennison et al., 2000; Feilzer AJ et al., 1987).

Figure 2.2: Curing light radiometer
Image source:
http://www.citicon.com.hk/products/optilux-radiometer-23/

The intensity of the curing light unit can deteriorate significantly by use over time and it is recommended that this is checked before each use by using a curing light radiometer (Poulos and Styner, 1997) (Figure 2.2), though this is not common practice. Changes in light intensity may occur as the distance increases from the tip of the light guide (Price et al., 2003); ideally, the tip of the curing unit should be within 1 to 2 mm of the restoration surface to obtain efficient curing. This concept cannot always be achieved in a clinical situation due to the anatomy of the tooth and the extension of the preparation margins. Light-transmitting wedges and light-focusing tips have been introduced in order to provide closer approximation of the curing light to the proximal composite restorations (Ericson and Derand, 1991; Ciamponi et al., 1994).

Inadequate curing may occur if the light source is not in close proximity to the surface of the material being polymerised as well as if the intensity of the light is inadequate or the light is attenuated by passing through a restoration or tooth substances (Strydom, 2002a; Dunne and Millar, 2008). Any of the previous reasons can result in a material with a hard outer ‘skin’, which is soft at the base of the preparation. Dentists should bear in mind that darker shades of resin composite materials absorb more light and therefore need longer curing times to obtain the same depth of cure as a lighter shade (Combe and Burke, 2000). When all these factors are considered, investigators advise prolonged curing times rather than shortened exposure times (Combe and Burke, 2000; Strydom, 2002a).

Light source exposure time can be considered as an important factor in reducing or at least minimising gap formation at the tooth/restoration interface. A number of studies have shown that increasing the depth of preparation can lead to a significant decrease in the effectiveness of the polymerisation of resin composite materials. In contrast, an extended exposure time of more than 40 seconds could result in greater extent of polymerisation (Yap, 2000).

2.3.3 Application techniques

The longevity of resin composite restorations not only depends on the composition of the materials but also to some extent to the handling and application technique as well as the skill of the clinician (Christensen, 2005).In other words, longevity seems to be reliant on many different interrelated factors which are the materials, the patient and the dentist (Hickel and Manhart, 2001).

Direct use of resin composites in posterior teeth has been shown to be a technique-sensitive procedure, especially with proximal restorations (Lyons, 2003). Careful technique at each step of application and placement may result in more accurate and predictable restorations and can also improve clinical performance (Lopes et al., 2004; Opdam et al., 1996). Moreover, the use and selection of suitable material with a controlled placement technique may reduce polymerisation shrinkage (Deliperi and Bardwell, 2002).

The effect of the application techniques of resin-based composite materials on microleakage was investigated by a number of researchers. A significant reduction in microleakage scores was reported when the material was placed

and cured in layers, whilst bulk placement generates more polymerization contraction stresses which inevitably lead to gap formation and subsequent bacterial infiltration (Nash et al., 2001; Poskus et al., 2004; Yamazaki et al., 2006). To establish a uniform and maximum cure it has been suggested that an increment of no more than 1.5-2 mm thick should be used with composite restorations (Fan et al., 2002).

2.3.4 The Geometry of the cavity preparation

The geometry of the cavity preparation, also known as configuration factor (C-Factor), defined as the ratio between the bonded and unbonded surfaces of the specimen (Feilzer et al., 1987) (Figure 2.3) can compromise the adaptation of the restorative material to the tooth preparation margins. It has been elucidated that “the less the restoration is bonded to opposing walls, the less obstruction there is for the shrinkage” (Davidson and Feilzer, 1997). C-factor has been reported to have a negative potential on dentine bond strength (Nikaido et al., 2002a; Nikaido et al., 2002b). Cavities with high C-factors have more potential risk of causing debonding within the resin-dentine interface (van Dijken, 2010). It is considered to be an influencing factor in the occurrence of microleakage (Hakimeh et al., 2000; Braga et al., 2006; Moreira da Silva et al., 2007; dos Santos et al., 2009; van Dijken, 2010; Alomari et al., 2011).

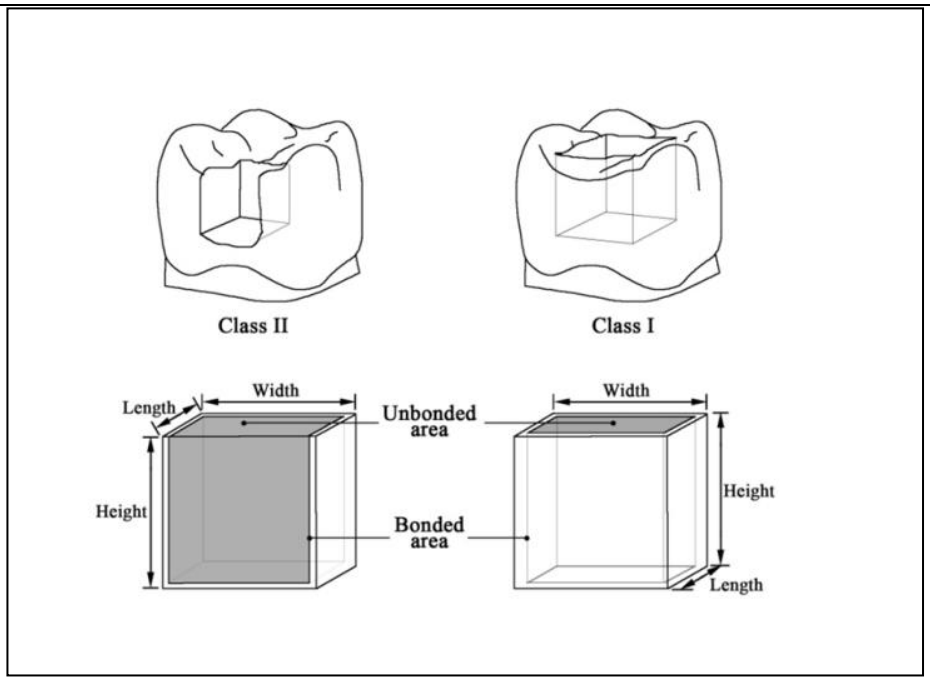


Image source: (Li et al., 2011)

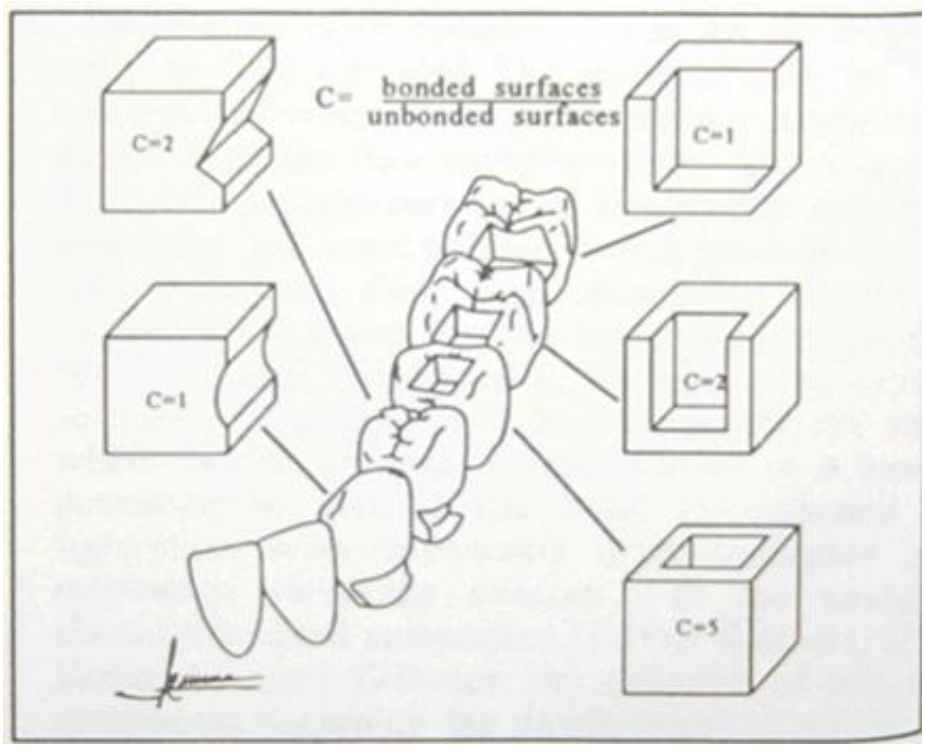


Image source:
(http://commons.wikimedia.org/wiki/File:C_factor.png)

Figure 2.3: C-factor (Ratio between bonded and unbonded surface of tooth restoration) in different cavity preparartion

2.3.5 Position of tooth preparation margin

The position of the preparation margins, in general, can affect the incidence of microleakage (Araujo Fde et al., 2006; Ozel et al., 2008). Resin composite restorations with margins located in enamel could exhibit consistent bonding and are less likely to show microleakage compared with those situated in dentine (Dietschi et al., 1995; Hilton et al., 1997; Ausiello et al., 1999; Dietrich et al., 1999; Araujo Fde et al., 2006). One of the weakest aspects with proximal restorations is the frequent placement of the margin apical to the cemento-enamel junction on dentine or cementum, where moisture control and access for finishing are more problematic. The oral environment, which includes moisture, physical stresses, changes in temperature and pH, dietary components, and chewing habits, has an apparent effect on the adhesive interaction between materials and tooth tissues (Summitt, 2006b). In addition to these factors, the deficiency of enamel at gingival margins, results in a less stable cementum-dentine substrate for bonding.

To explain this, from a theoretical point of view, enamel near to or close to the cemento-enamel junction is usually thin, aprismatic and shows weak bonding compared with occlusal enamel. This may explain gap formation at the interface with dentine or cementum where the bonding is much weaker than that to the occlusal enamel. This can be explained by the fact that when the resin composite polymerises, it shrinks toward the stronger bond at the occlusal margin and away from the weaker bond at the gingival margin (Jorgensen et al., 1985; Hansen, 1982; Brannstrom et al., 1984). This could explain, in part, the

difficulty of finding a solution to the problem of microleakage, especially in restorations with margins below CEJ where it is difficult to obtain moisture control.

2.3.5 Adhesion to the tooth structure

A series of papers have dealt with the influence of adhesive systems on the extent of microleakage. Harada and co-workers (2006) have studied the effect of the number of coats of different adhesive systems on dentine margin microleakage. They concluded that all adhesive systems demonstrated microleakage; however, this could be minimized by using two coats of non-filled or one coat of a filled adhesive bonding system. The total-etch adhesives revealed significantly less microleakage scores than the self-etching adhesive systems in a clinical based study of cervical restorations (Koliniotou-Koumpia et al., 2004). Using 37% phosphoric acid has been shown to be effective in reducing microleakage significantly compared with the use of a dentine conditioner as polyacrylic acid (Retief et al., 1992). It also permits the total removal of the smear layer compared with other concentrations and other etching agents (Rontani et al., 2000). It has also demonstrated higher shear bond strength values, regardless of the adhesive system. Some recently introduced methods for etching the preparation walls using a laser technique illustrated extreme marginal leakage compared with acid etching using 37% phosphoric acid (Ceballos et al., 2001; Yazici et al., 2001). The OptiBond Solo adhesive (total etch adhesive) was the most effective in reducing microleakge at

the dentin margins when compared with self-etching adhesive system (Arias et al., 2004).

2.4 Bonding resin based restorative material to the tooth structure (Enamel and Dentine):

In terms of bonding resin based material to enamel, the mechanism of bonding to enamel basically is an exchange process involving replacement of the minerals from the etched tooth tissues by resin monomer which becomes micro-mechanically interlocked in the created porosity. Thus, a secure, strong and durable micro-mechanical bond is achieved (Swift et al., 1995a; Buonocore, 1955). Buonocore (1968) suggested that resin tag formation was the main element in the adhesion between resins and acid etched enamel, in which resin penetrates the microporosities of etched enamel and leads to a micromechanical bond.

In dentine, the primary bonding mechanism of the adhesives is primarily diffusion-based and depends upon hybridization or micro-mechanical interlocking of resin within the exposed collagen fibril (Peumans et al., 2005; Nakabayashi et al., 1982). Adhesion to dentine however, is more problematic (Perdigao et al., 2000) and there is little evidence of chemical bond formation to dentine using currently available adhesive systems. Therefore, they are still unpredictable and require further work, in order to generate an efficient

adhesive system capable of adequate interaction with this delicate structure (Eick et al., 1991; Lopes et al., 2003).

In order to achieve an optimally bonded interface, clinicians should bear in mind certain requirements. These include that, firstly, the surface of the tooth substrate should be clean and free from any debris or what is called the smear layer. Secondly, the applied adhesive should wet the surface well and be cured properly to avoid under-curing (Craig et al., 2006). Smear layer removal by acid etching has been recommended in order to enhance adhesion and subsequent adaptation of resin composite or resin modified glass ionomer cements to the enamel and dentine surface. In addition, it can be effective in minimising bacterial microleakage (Murray et al., 2002).

2.4.1 Adhesive system:

At the present time, three main approaches to dentine bonding are advocated and classified according to the adhesion strategy and clinical steps in their application (Eliades et al., 2005; De Munck et al., 2005). They include etch & rinse; self-etch; and resin modified glass ionomer adhesive.

Following cavity preparation, a smear layer is created on the prepared surface. This layer can be either totally removed by using etch and rinse option or it can be left over the surface using an adhesive that can penetrate the smear layer following the self-etch approach (Van Meerbeek et al., 2003).

With regards to the total etch approach (Etch and rinse); firstly, the tooth is etched (mostly 30–40% phosphoric acid) and rinsed off. This step is followed by a priming step and application of the adhesive resin, resulting in a conventional three-step application procedure. In an attempt to simplify the three step procedure a two-step etch and rinse adhesive system (often known as 'one-bottle' adhesive) in which the primer and adhesive are combined into one application was developed (Peumans et al., 2005). The efficiency of the acid etching process is dependent on type, concentration of the used acid and the duration of the acid etching procedure (Kugel and Ferrari, 2000).

Bonding efficiency can be affected by other factors, including moisture contamination and incomplete infiltration of resin into the demineralized layer of the tooth tissues. The latter may result from excessive etching or over-drying, which causes the collapse of collagen fibrils (Bouillaguet et al., 2001). These could consequently have a negative impact on the material's ability to achieve an effective seal at the gingival margin (Stockton and Tsang, 2007).

The major drawback of etch & rinse adhesives is its technique sensitivity and lengthy working procedure. Most of the laboratory based studies employed the technique on flat dentine surfaces in which a relatively uniform surface wetness can be obtained. The clinical situation has, however, shown a different scenario in which it is inevitable that over drying of the pulpal or axial wall of complex cavities occurs whilst water pools at cervico-axial line angles (too wet to achieve perfect bonding). This results in a non-uniform degree of surface wetness and

uneven resin infiltration. This may explain why the technique was found to increase microleakage and clinical sensitivity especially at the gingival floor of proximal boxes (Pashley, 2003) when compared with the flat dentine surface which is mostly used in the laboratory based studies.

In the self-etching systems, there is no need for using a separate acid etch step which eliminates the need for rinsing (Sensi et al., 2005). Following this approach, the non-rinse acidic monomers are incorporated in the adhesive system and used to condition and prime enamel and dentine. It was assumed that this approach could lessen the clinical application time and noticeably reduces technique sensitivity (Peumans et al., 2005). Self-etching systems exhibited low bond strength and a high rate of spontaneous failure as reported by Perdigao et al (2006), meanwhile, the "total etch" technique has been shown to provide better results (Perdigao et al., 2006; Salim et al., 2006).

Thus far, research has indicated that etch and rinse approach is the most effective in achieving an efficient and stable bond to enamel and dentine (Shirai et al., 2005). In comparison with self-etch adhesive techniques it produces the most reliable bond in the longer-term (van Dijken, 2000; Bouillaguet et al., 2001; Inoue et al., 2001; Van Meerbeek et al., 2003; Peumans et al., 2005).

Considerable research has gone into improving the formulation, marginal quality and sealing ability of adhesive systems. Filler particles have been incorporated in the adhesive system for the purpose of increasing the adhesive strength,

modifying the viscosity, and to act as a stress buffer to release stress generated during polymerisation shrinkage. They have also provided a radio-opaque particle which allows detection of adhesive resin on the dental x-ray film and avoid misinterpretation of the unfilled adhesive radiolucency to gap formation or recurrent caries which may require restoration replacement (Mirmohammadi et al., 2014; Can Say et al., 2006). Though, filled adhesive was reported to yield dentine bond strength equivalent to or more than that of the unfilled adhesive (Gallo et al., 2001). Filled adhesive has demonstrated a thick adhesive layer when compared with unfilled adhesive due to its increased viscosity (Grossman and Setzer, 2001). The thickness of the adhesive required in resin composite restoration is still a matter of debate. An adhesive layer of a thickness more than 100 µm was reported to have a substantial effect in stress reduction and was claimed to improve marginal integrity of the restoration as reported by Choi et al (2000) and this is in contrast to the manufacturer's recommendation of a thin layer. They have found that uniform adhesive thickness is only possible on a flat tooth surfaces. Three dimensional cavities may show a different distribution of the adhesive as thin adhesive could be seen in the margin of the cavity, a thick layer was more pronounced in the floor, angle and in the irregular surfaces of the cavity. That was attributed to the gravity and surface tension effects. It was postulated that a high concentration of stress and an increased possibility of leakage at the margin of the restoration can be attributed to the thin adhesive layer (Choi et al., 2000). This finding was in agreement with the finding of Opdam et al (1997). Studies by other researchers have reported the opposite and found that thick adhesive leads to increased crack propagagtion

and reduced bond strength (Hilton and Schwartz, 1995; de Menezes et al., 2013).

Bonding to dentine is still problematic and challenging compared with bonding to enamel (Kugel and Ferrari, 2000; Lopes et al., 2002; Perdigao, 2002). Improvement of the bond strength of restorative materials is not only dependent on the adhesive system but could also be obtained by appropriate tooth preparation and careful positioning of increments of resin composite during placement (Yoshiyama et al., 1996; Carvalho et al., 1996; Andersson-Wenckert et al., 2002; Owens and Johnson, 2005)

To date, microleakage is still considered to be one of the major problems associated with proximal composite restorations especially when the margin is at or below the cemento-enamel junction (Araujo Fde et al., 2006; Xie et al., 2008; Majeed et al., 2009). Therefore, many in-vivo and in-vitro studies have been conducted, aimed at eliminating or at least reducing microleakage, in order to prevent restoration failure and increase their long term success (Al-Saleh et al., 2010; Kasraei et al., 2011; Hafer et al., 2013).

2.5 Techniques used to control microleakage in posterior resin composite restorations

In an attempt to address the problem of microleakage, a number of techniques have been proposed, such as indirect restorations (inlay type) (Robinson et al., 1987; van Dijken, 1994; Duquia Rde et al., 2006), the use of fibre inserts (El-

Mowafy et al., 2007), the use of surface sealant (Silva Santana et al., 2009), preheating resin (dos Santos et al., 2011), the use of different light curing units, intensities, curing times and curing protocols (Amaral et al., 2002; Cavalcante et al., 2003; Danesh et al., 2004; Fleming et al., 2007; Hardan et al., 2008; Froes-Salgado et al., 2009; Hardan et al., 2009). The sandwich restoration technique is one of the proposed procedures to relieve the contraction stress of direct resin composite restoration.

2.5.1 Sandwich restoration technique (Bonded base restoration)

“Sandwich” restorations, also referred to as a bonded base restoration, was first presented by McLean (McLean and Wilson, 1977) and was suggested with the intention of improving marginal integrity of direct resin composite restorations, especially when the cervical margin was situated in dentine. Conventional glass- ionomer cement was used to seal the cervical dentine, the cement was acid etched; subsequently a thin coat of resin bonding agent was applied, cured and a resin composite material was then inserted (McLean et al., 1985; Welbury and Murray, 1990).

The sandwich restoration can be placed in two different manners one called a closed sandwich technique in which the cement replacing the cervical portion was completely covered with the resin composite materials. Alternatively, cement can be extended to the periphery of the proximal box exposed to oral environment over which the resin composite is placed, in what is called an open sandwich technique (Knibbs, 1992; van Dijken, 1994).

Several restorative materials have been suggested as lining materials in deep and moderate proximal cavities where resin composite sandwich restorations are considered. Among these are glass ionomer cement, resin modified glass ionomer materials, compomer (polyacid modified composite resins) (Wucher et al., 2002; Lindberg et al., 2003) and flowable composites (Hagge et al., 2001). However, their long-term efficiency as cavity liners on enhancing marginal adaptation is still limited, (Wibowo and Stockton, 2001; Moazzami et al., 2014).

Conventional glass ionomer cement has the drawback of being hydrolytically unstable in the early stage of setting and sensitive to water uptake (Ngo et al., 1997).

High clinical failure rates after 6 years have been reported with the traditional sandwich technique when conventional GIC was used as the base (van Dijken, 1994). Failure was due to dissolution of the GIC and continuous loss of material due to early moisture contamination.

The effect of using a flowable resin composite liner on the interfacial adaptation of the restoration was studied in-vivo in an attempt to improve adaptation and decrease microleakage. The study investigated the clinical performance of a resin composite material with and without a flowable composite liner, but showed no clinical benefit from using a flowable liner (Lindberg et al., 2005). This finding is in agreement with more recent result by Fabianelli et al. (2010)

who reported that flowable resin composite was not able to prevent dye penetration when placing sandwich restoration. More recently, the use of an intermediate layer of flowable resin after the adhesive application has shown a slight improvement to the bond strength and marginal sealing to dentine. This technique has however, displayed an increased cohesive failure percentage when using flowable composite (Abdalla, 2010).

Dual cure composite has recently been used as a dentine substitute with the sandwich technique and showed microleakage reduction when delayed light activation was employed (Atlas et al., 2009). Delayed light polymerization of a dual cured composite base was one of the suggested methods when employing the sandwich restoration, as delayed curing has demonstrated that the self-cure mode yields a lower polymerization contraction stress than light-cure mode (Feng and Suh, 2006; Kamath et al., 2012). However, the use of dual cure composite (Koubi et al., 2010) has exhibited a higher microleakage score when compared with the use of resin modified glass ionomer cement, the water sorption properties of which may help to relieve polymerisation shrinkage. Koubi et al. (2010) have stressed that RMGICs remains the best intermediate material when open-sandwich restorations are implicated.

Resin-modified glass ionomer restorative materials were introduced in the late 1980s by Mathis and Ferracane (1989) to overcome the disadvantages of traditional glass ionomer cements and to increase the number of clinical applications as an alternative to conventional glass ionomer cements (Uno et al., 1996).These materials are used as a liner or base and can be valuable in

controlling microleakage (Davidson and Feilzer, 1997). They have three main setting reactions; a glass ionomer acid /base reaction, a resin light activated polymerization reaction and an auto-cure initiator-catalyst for the resin (Christensen, 1997). A light cured system was incorporated in these materials for the advantage of reducing setting time (Mount, 1994). The three curing phenomena allow the material to set, even if the restoration extends into areas inaccessible to light curing (Christensen, 1997).

The introduction of resin modified glass ionomer materials has made a significant impact on the practice of restorative dentistry. Compared with their conventional predecessors, they demonstrated better aesthetic properties and are less technique sensitive. They have been shown to be less sensitive to contamination with saliva and blood during the bonding procedure compared with conventional glass ionomer cements (Dietrich et al., 2000c). Moreover, RMGICs exhibit higher bond strengths with resin composites (Taher and Ateyah, 2007) and have shown a reliable adhesion to both enamel and dentine, depending on the so called absorption layer which is formed immediately after water sorption (Triana et al., 1994; Pereira et al., 2002; Palma-Dibb et al., 2003). This, as reported by Tay et al (2004), mediates better bonding of RMGIC to deep dentine, and functions as a stress-relieving layer to reduce stresses induced by desiccation and shrinkage. Resin-modified glass ionomer cements are proposed to be more tolerant of "temperature/relative humidity" parameters when compared with the conventional glass ionomer cement (Besnault and Attal, 2003). Furthermore, they have a propensity for enhancing mechanical properties (compressive and flexural strength) over a 24-h period and

subsequently maintain a constant strength (Miyazaki et al., 1996). The use of these materials in the sandwich technique as reported in the literature (Suzuki and Jordan, 1990; Wilson, 1990; Loguercio et al., 2002; Tantbirojn et al., 2009), can improve chemical adhesion to dentine and micromechanical bond to the overlying resin. Additionally, RMGICs were shown to preserve the sealing integrity of the restoration and exhibited a low marginal microleakage (Chuang et al., 2003).

There are relatively few long-term in vivo clinical trials reporting on sandwich resin composite restorations. However, this technique has been well documented in several in vitro studies.

The first reported clinical trial concerning application of conventional glass ionomer cement with resin composite in sandwich restorations was reported by Welbury and Murray (1990). Forty-nine proximal restorations, placed in permanent premolar and molar teeth of 23 patients, were studied over a 2-year period. The margins of the prepared boxes were all in enamel. This technique failed however, to provide acceptable restorations as the vast majority of the restorations failed due to progressive loss of glass ionomer cement. This finding is in line with the findings of Van Dijken (1994), who also reported a 75% failure rate of open bonded-base resin composite restoration after 6 years evaluation. This, in turn, confirmed the findings of an early study by Knibbs (1992), in which he concluded that this type of filling cannot be advocated for the restoration of proximal lesions.

Van Dijken et al. (1999) conducted a clinical trials aimed at evaluating the durability of modified open sandwich restorations in large cavities, using resin modified glass ionomer cement. The numbers of the restorations were 274 class II formed by 4 dentists in 168 adults to replace failed large amalgam restoration. The cement was either applied as a thick or thin layer after cavity conditioning with polyacrlyic acid or maleic acid. They evaluated the restorations at baseline and after 6, 12, 24, and 36 months. They concluded that the modified version of sandwich restorations using resin modified glass ionomer as an intermediate layer can perform better than the conventional GIC/resin composite laminates and resulted in good clinical quality and low failure rate of 5% after three years in clinical service. They have however; found that the numbers of failure rates were increased to 19% after 6 years (Andersson-Wenckert et al., 2004). The most common reasons cited for the failures were tooth fracture, and secondary caries following slight dissolution of the RMGIC. Opdam et al. (2007) also observed the same reason for failure, which was more pronounced after a period of more than three years, in a retrospective study for a 5 year observation period. In addition, more failures were found in restorations with cervical margins in dentine than those with enamel bordered margins. The use of polyacrylic acid to condition the cavity has been shown to contribute to the higher failure rate of the restorations when compared with the use of the maleic acid. This finding confirmed the finding of Hinoura et al. (1991) who showed that polyacrylic acid conditioning lowered the shear bond strength of RMGIC whereas maleic acid gave a better shear bond strength. This study also demonstrated increased failure rates when a thick layer of cement was used. The size of the cavities and also the position of the

cervical margin were not standardized and were predetermined by existing amalgam restorations. These large undermined amalgam cavities may have contributed to the tooth fracture (van Dijken et al., 1999). The operators' skill could also be considered to have a great effect on the longevity of restorations (Kubo et al., 2011) as 4 dentists were placing the restorations.

Aboush et al (2000), after a one year clinical evaluation of the same technique (resin composite/resin modified glass ionomer open sandwich restoration) in comparison to the total bond resin composite restorations, reported no significant differences in the clinical performance of the two types of the restorations. The dimensions of the preparations, however, were not standardized and were predetermined by the extent of the carious lesion or the existing restorations. This could have had an impact on the outcome of the results and could also influence the quality of adaptation of the restorative materials (Van Meerbeek et al., 1994). Moreover, a one-year study gives limited insight into the potential clinical service of such restorations. The sample was composed of different type of teeth (molar and premolar) which has shown to have a significant effect on the longevity of the restorations (Kubo et al., 2011). Premolar teeth could show a better survival rate than the molar teeth when considering the greater occlusal forces on molar restorations compared with that on the premolar restorations (Opdam et al., 2007) and also the accessibility to the operating field which may affect the size of the preparation (Kubo et al., 2011).

Andersson-Wenckert and colleagues (2002) conducted a clinical study aimed to evaluate the durability of sandwich restorations interface of RMGIC/RC when compared with the resin composite restoration. The number of restored teeth was 20 premolars scheduled for extraction after one month for an orthodontic reason. They had reported a significant difference in gap formation and found a gap free adaptation to dentine in 81.5% and 65% for RMGIC/resin composite and resin composite restorations respectively. They concluded that RMGIC sandwich restorations have better adaptation to the dentine and cervical enamel than resin composite. This difference when compared with previous study by Aboush and colleagues (2000) may be explained by the difference in study design as they used 20 premolar teeth that were free of caries. This result has been confirmed with many in vitro studies which have shown that using the bonded-base technique in proximal and cervical restorations may significantly reduce marginal leakage when compared with total bonded resin composite restorations (Miller et al., 1996; Friedl et al., 1997; Dietrich et al., 1999; Dietrich et al., 2000a; Loguercio et al., 2002).

Despite the efforts exerted by a number of investigators, to reduce microleakage with resin composite restorations, polymerization contraction still occurred and the consequent microleakage could not predictably be prevented by the use of this technique (Dietrich et al., 2000c). Conclusive clinical evidence for the efficacy of the sandwich technique to restore proximal posterior preparations is still lacking (van Dijken, 1994; Lindberg et al., 2000; Lindberg et al., 2007). Simultaneous curing (co- curing) of the restorative material with resin

composite sandwich restoration was proposed to have an effect in reducing the stress generated during polymerization.

2.5.2 Co-curing technique with sandwich restorations:

The co-cure technique, which was introduced in the early 1990s, had been anticipated to reduce both technique sensitivity and placement time (Knight, 1994). Co-curing was defined as the simultaneous photo polymerization of two different light activated restorative materials and claimed to decrease the internal stresses in composite restorations (Knight et al., 2006). The initial concept of co-curing emerged after an accidental observation of the effect that a two seconds light cure of glass ionomer cement and resin composite located together on a glass slab, had on the hardness of the two materials. While the resin composite exhibited a hardened surface, the glass ionomer cement stayed a viscous paste. It was suggested therefore that as the resin composite is activated before the glass ionomer cement, the polymerization shrinkage which leads to dimensional changes in the resin composite could be compensated by the uncured glass ionomer when the two materials are employed in the sandwich restorative technique. In view of that, co-curing may perhaps help to eliminate the internal stresses in the restoration and reduce marginal leakage (Knight, 1994). It has also been found that delaying the polymerization of resin modified glass ionomer may improve marginal integrity (Khoroushi et al., 2012b).

The co- cure technique has been tried with different adhesive systems when placing direct resin composite restorations. Tulunoglu et al. (2000), reported

that co-curing the adhesive with the resin composite did not produce any significant increase in microleakage when compared with the pre-curing technique using different adhesive systems (total etch and self-etch adhesive), in class V resin composite restorations. The same technique has been assessed recently by Chapman et al. (2007) who used three self-etch adhesive system applied on a flat dentine and enamel surface by either curing the adhesive material first and then curing the overlying resin composite or simultaneously curing the two materials. They found that co-curing the adhesive and composite resulted in decreased bond strength to dentine in comparison with separate curing. The reason behind that was demonstrated by the investigators as follows; curing resin composite generated stress, which may affect the penetration of the resin tags into the dentinal tubule and lead to a weak bond that cannot withstand polymerisation stress.

Boruziniat and Gharaei (2014) investigated the bond strength between RMGIC and composite and employed the simultaneous curing concept with sandwich restoration by simultaneous curing RMGIC and different adhesive systems. Their assumption was that co curing of the two materials (RMGIC/adhesive) may increase penetration of adhesive systems into RMGIC before curing and so enhance bond strength. They concluded that the co-curing increased shear bond strength of RMGIC to dentine when using self-etch adhesive, yet reduced it when total etch adhesive was employed. In the total-etch pre-cured group they observed severe cracks and voids in the composite-adhesive interface while in the co-cured group of this adhesive, severe crack and voids appeared in the RMGI-adhesive interface. This finding was in agreement with other

studies (Kerby and Knobloch, 1992) which reported that, the acid etching required with the total etch adhesive system may lead to a partial elimination of HEMA and un-reacted methacrylate groups in the air-inhibited layer and consequently decrease the bond strength when applied over a cured RMGIC.

A recent study by Shafiei and Akbarian (2014), on the effect of simultaneous curing, of nano-glass ionomer cement with nano adhesive using a modified sandwich restorations, on microleakage, have concluded that the technique has shown similar effect in terms of cervical sealing when compared with total bonding restoration. They have both shown good marginal seal. It has also demonstrated a significantly lower microleakage and reduced clinical application steps and time when compared with conventional sandwich restoration. The advantages of using this type of material were the slow polymerization reaction in which the viscous flow of the molecules may have a high potential for relieving stress associated with polymerization shrinkage.

Resin modified glass ionomer Cements have been credited with the ability to truly adhere to both enamel and dentine via a specific glass-ionomer interaction. Their adhesion to tooth tissue includes both chemical adhesion between calcium in hydroxyapatite and polyalkenoic acid (acid/ base reaction), and micromechanical hybridization through subsequent infiltration and mechanical interlocking (Van Meerbeek et al., 2000). This type of material has the advantage of having a self-adhesive, biocompatible and cariostatic potential through fluoride release, which encourages remineralization of the adjacent

calcified dental tissues (Wiegand et al., 2007; Tantbirojn et al., 2009; Basso et al., 2011). Coutinho et al (2007) concluded that self-adhesiveness of RMGICs is generally claimed to be dependent not only on ionic bonding to hydroxyapatite around collagen, but also to micro-mechanical interlocking for RMGICs that additionally hybridize dentine. On the other hand, numerous previous studies have reported that bond strength of resin modified glass ionomer cements to the tooth structure were greater than those of conventional glass-ionomers (Mitra, 1991; Friedl et al., 1995; Swift et al., 1995b) but with a level of adhesion less than that obtained with composite restorations bonded with adhesive systems (Fritz et al., 1996; Khoroushi et al., 2012a).The use of adhesive systems when compared with a conventional cavity conditioner (polyacrylic acid) has shown to improve the marginal integrity of cervical RMGIC restorations at dentine margins (Khoroushi et al., 2012a) that was explained by the presence of resin components in both the adhesive and resin modified glass ionomer which allows for covalent bond formation between the two materials. The combination of the adhesive system with resin modified glass ionomer to adhere to the dentine was recommended by many previous researchers (Pereira et al., 1998; Besnault et al., 2004; Geerts et al., 2010; Dursun and Attal, 2011; Poggio et al., 2014) for the benefit of increasing the bond strength of resin modified glass ionomer to dentine as an alternative method to the conventional dentine conditioner which provides a lower bond strength to dentine. As stated by Dursun and Attal (2011), both the adhesive material and the Fuji (RMGIC) contain a constituent with unsaturated carbon-carbon bonds which allow for a direct covalent bonds to be achieved between the two materials after

polymerization. They proved this alternative approach to be a very promising technique for the ionomer/tooth interface.

When the sandwich restoration was considered, resin modified glass ionomer cement, showed a higher bond strength to the overlying resin composite (Li et al., 1996) as the hydroxyl-ethyl-methacrylate (HEMA) content of resin modified glass ionomer cement (Wilson, 1990; Fortin et al., 1995) forms a chemical bond with the resin composite (Summitt, 2006a) and for that reason etching is not required for bonding the cement with resin composite (Farah et al., 1998). According to Tale et al. (1996), acid etching of RMGIC has no effect on bond strength, and could even decrease shear bond strength of this cement to resin composite material (Sidhu and Watson, 1995). This finding was supported by Taher and Ateyah (2007) who pointed out that RMGICs are not influenced by acid etching owing to their high resin content. That has allowed for further reduction of the time required for sandwich restoration application. The literature has reported contradictory results regarding the effects of acid etching on bond strength of RMGIC to composite although some reported that etching of RMGIC may have no effect (Taher and Ateyah, 2007; Navimipour et al., 2012), others have found adverse effects (Kerby and Knobloch, 1992), or improved bond strength (Brackett and Huget, 1996).

The placement of the restorative material using a sandwich technique, however, appears to be technique sensitive and time consuming and showed a higher microleakage when compared with the incremental techniques (Moazzami et al.,

2014). Even with a newly introduced material, (commercial name Biodentine) tricalcium silicate, significant leakage was reported when compared with the resin modified glass ionomer cement (Camilleri, 2013).

2.6 Assessment of microleakage

Microleakage is one of the parameters that have been in use by dental researchers to assess the adaptation of dental restorative materials to prepared teeth. The extent of microleakage around restorations can be investigated in vitro, either on extracted teeth or artificial models. Many techniques have been proposed to test microleakage in vitro. The techniques conducted in vitro have included: the use of dyes, chemical tracers, radioactive isotopes, air pressure, bacteria, neutron activation analysis, scanning electron microscopy, artificial caries techniques, and electrical conductivity (Powis et al., 1988; Going et al., 1968; Going, 1972; Chan and Jones, 1992).

2.6.1 Dye penetration test

The dye penetration test is one of the most commonly used methods for detecting microleakage in vitro, due to its speed of obtaining results and its ease of implementation (Camargo DA, 2002; Taylor and Lynch, 1992). There are a wide variety of dye materials used in an in-vitro testing of microleakage including rhodamine b, methylene blue, basic fuschin, and silver nitrate and many more (Mente et al., 2010). With the dye penetration test, a number of different protocols have been used: sectioning the specimens into single or

multiple longitudinal slices (Gwinnett et al., 1995) or using clearing protocol (Robertson and Leeb, 1982; Saunders and Saunders, 1990).

One of the most commonly used tracers in microleakage studies is silver nitrate which has the advantage of strong optical contrast of the silver particles (Gonzalez et al., 1997) and has been shown to penetrate the dentinal tubules to a similar extent to other commonly used tracers (Eosin, methylene blue, indian ink) (Youngson et al., 1998).

The wide variety of dye materials used in an in-vitro testing of microleakage, has produced conflicting findings and difficulty in comparing many of the study outcomes (Dejou et al., 1996) as they lack standardisation of the parameters. Accordingly, it has been advocated that comparison of studies using different tracers should be avoided (de Almeida et al., 2003).

2.6.2 X ray Micro computed tomography (Micro CT)

Micro computed tomography is a computer-aided 3D reconstruction of the structure of a material. It is a non-invasive, non-destructive tool used to visualize the structure of the object. The development of this system was referred to as long ago as the early 1980s. It has a high resolution in the range of 5-50 μm. Its use can include examination of a wide range of specimens, for instance mineralised tissue such as teeth, bone and also many types of materials including ceramic, polymers, biomaterial scaffold, etc. Its use indicated within different scientific fields such as cancer diagnosis, engineering.

This tool has received more significant consideration in dental research during the last decade (Swain and Xue, 2009; Mackerle, 2004). The dental literature has shown many applications of this technology which incorporates measurement of tooth and enamel thickness (Olejniczak and Grine, 2006), analysis of root canal morphology (Oi et al., 2004) and evaluating mechanically stressed dentine- adhesive- composite interfaces (De Santis et al., 2005).

Micro CT scanning can provide a large range of information, help in the generation of a more precise finite element model of a small object such as a tooth, dental implants and dental restorations (Verdonschot et al., 2001). Imaging from Micro CT scans can be classified as either two dimensional (2D) or three dimensional (3D) images and can be assessed both qualitatively and quantitatively. Images can be recreated and displayed in any plane (Dowker et al., 1997). The internal features of the same sample may be examined many times and the sample remains available after scanning for additional testing (Swain and Xue, 2009).

The advantage of this method in investigating microleakage is that the sample is not destroyed as in the commonly used traditional sectioning technique; the deepest point of tracer penetration can be assessed therefore providing more accurate measurement of the maximum depth of marginal leakage (De Santis et al., 2005).

Chen et al (2010) employed Micro CT scanning techniques to compare marginal leakage of various sealant materials at the sealant enamel interface

using 50% silver nitrate as a tracer. The 2D image generated was not clear enough to allow assessment of the total area of the non-bonded surface which was attributed to the density of the sealant rather than the accuracy of the image. De Santis et al. (2005) used it to evaluate mechanically stressed dentine-adhesive- composite interfaces. They concluded that the X-ray micro-CT technique is a very powerful tool to investigate silver nitrate leakage at the dentine bonding/composite interface, providing very sharp images of the silver ions penetration at tooth–restoration margins. Moreover, depth of dye penetration can be analysed in a non-destructive manner.

2.6.3 Thermocycling

The vast majority of microleakage studies have included a Thermocycling test, which is a regime of artificial aging of a dental restoration by transferring the specimens from hot to cold solutions (Kidd et al., 1978) in order to simulate the thermal changes which occur in the mouth during eating, drinking, and breathing (Gale and Darvell, 1999). This method promoted an iterative procedure of contraction/ expansion stresses loaded on the tooth-restoration interface by subjecting it to warming and cooling which may lead to crack propagation, gap formation (Amaral et al., 2007) and microleakage at the tooth-restoration interface (Momoi et al., 1990). The difference in the coefficients of thermal expansion between the restorative materials and the tooth structure is the reason behind the thermally induced stresses at the tooth restoration interface which may lead to gap formation and microleakage (Nelsen et al., 1952). This concept constituted the early basis for using Thermocycling in terms of simulating the temperature changes in the oral cavity (Wendt et al., 1992).

A reduction or no change in microleakage pattern following Thermocycling led others to suggest that when resin composite restoration is considered, thermal percolation may have no clinical significance (Kidd et al., 1978) attributing that to increased water sorption (Yap and Wee, 2002; Fujii et al., 1999) which may allow for relaxation of the polymerization stresses and compress the composite restoration against the cavity wall (Harper et al., 1980) and on the other hand may lead to staining and breakage in the marginal contour of the restorations.

A debate can be inferred from reviewing the literature on the advantages and disadvantages of utilising a Thermocycling regime in microleakage studies. Some researchers support the use of Thermocycling in order to simulate the thermal element of the intra-oral situation which could generate stresses on the restorative materials (Momoi et al., 1990) and consequently lead to increase in the microleakage (Cooley and Barkmeier, 1991; Wahab et al., 2003). Others however, have reported no significant increase in microleakage when Thermocycling was used (Wendt et al., 1992; Bijella and da Silva, 2001). The test has however, been very questionable in terms of validity and clinical significance (Kidd et al., 1978; Wendt et al., 1992; Harper et al., 1980) as the temperature extremes that are used in the test may not be true simulation of the real temperatures of food and beverages that can be tolerated by oral tissue and are suitable for clinical conditions. The wide range of the temperature extremes, transfer times between baths, number of cycles and dwell time as reported in the literature (Nalcaci and Ulusoy, 2007) has shown no standardization for Thermocycling methodology employed in microleakage studies. The lack of general agreement on a definitive thermal cycling regime

has led some researchers to refrain from the use of thermal cycling (Youngson et al., 1991). Others have suggested combining the Thermocycling with load-cycling to facilitate comparison between clinical and laboratory investigation (Qvist, 1983).

Systematic reviews of Thermocycling procedures for laboratory testing of dental restorations (Gale and Darvell, 1999) found that the mean low-temperature point used for Thermocycling tests was 6.68C (range 0 –36.8C, median 5.08C) and the mean high temperature point was 55.58C, with the vast majority of the researchers using just hot and cold temperatures points. Some were using an intermediate temperature of 37.8C. An enormous variation in the number of cycles was reported with a mean of about 10 000 and median of 500 cycles, with a dwell time (i.e. the duration of thermal insult) ranging from 4 seconds to 20 minutes. Dwell time of exposing the specimens to extreme temperature ranges in the water baths has shown to be different amongst the in vitro Thermocycling tests. A difference in the number of thermal cycles from 250 to 1000 cycles revealed no significant difference in microleakage (Mandras et al., 1991; Pazinatto et al., 2003).

Previous work supported that a short dwell time of 30 seconds or less in resin composite restorations even for an increased number of cycles for up to 5000 cycles revealed no significant difference in the extent of leakage (Retief et al., 1988; Mandras et al., 1991). Rossomando and Wendt (1995) attributed this finding to the insulating properties of the resin based “plastic” restorations,

which showed good thermal insulating properties in comparison to amalgam based restorations. An extended dwell time should not be considered clinically relevant (Rossomando and Wendt, 1995) as the patient is unable to tolerate extreme hot or cold substances for an extended period of time (Harper et al., 1980).

Lowering the number of cycles could minimize the effect of other variables which include water sorption and possible hydrolization of the bond of the dentine bonding agent (Wendt et al., 1992). Excessive stresses for a longer time could have poor unreasonable influence on materials which may serve perfectly well in practice. Additionally, to represent the typical situation of thermal changes in the oral cavity, sufficient time should be allowed for the restoration to return to the reference resting temperature in order to avoid sudden alteration from one to the other extreme temperature (Gale and Darvell, 1999).

In conclusion, a fluctuating thermal cycle has been included in the vast majority of laboratory tests investigating microleakage, marginal gap, and the bond strength of dental materials. There was, however, a lack of any apparent justifications or standardization for the protocols used. Most of Thermocycling reports published are inconsistent and contradictory (Leloup et al., 2001; Amaral et al., 2007).

As stated by the International Organization for Standardization on their guidance on testing of adhesion to tooth structure (ISO, 2003) Thermocycling

test should comprise 500 cycles in water between 5 ^{o}C and 55 ^{o}C. The exposure time in each bath should be at least 20 seconds, and the transfer time should be 5 seconds to 10 seconds.

2.7 Finite element analysis and its use in dentistry

Finite element analysis is a computational numerical method that is currently widely used in all forms of engineering including civil, aerospace and automated nuclear engineering and many more fields since its development in 1956 (Turner et al., 1956).

Its use in dentistry for stress analysis was referred to as far back as the 1970's (Thresher and Saito, 1973). The application of this method in dentistry included orthodontics, prosthodontics, oral and maxillofacial surgery, implantology, periodontology, endodontology and restorative dentistry (Fennis et al., 2004). In conducting dental research, the finite element analysis (FEA) has become an important tool to identify the failure mechanisms of resin based restorations and may help to suggest possible alternatives which could minimize failure (Rodrigues et al., 2011).

This method has become more commonly used owing that to the ease of modelling and simulating more complex geometries and the possibility of providing greater insight into the internal stress of both tooth and restorations. It permits modelling the mechanical properties of tooth structure, restoration, stress and strain and also enables the investigator to isolate variables of

interest to study their individual effects and in turn compare it with other variables if needed (Rodrigues et al., 2011). Finite element (FE) modelling however requires experimental validation in order to support the generated results and also necessitates the help of an expert engineer who has mastered this technique (Shetty et al., 2010; Chuang et al., 2011).

The technique is based on the concept of building a complicated object with simple blocks, or subdivisions of a complicated object, into small and manageable pieces of a simpler geometric shape (elements) which are interconnected at a finite number of points (nodes) (Selna et al., 1975). There are two types of Finite Element Analysis employed by researchers in this field; these are two and three dimensional modelling (2D and 3D). Adoption of a 2D or 3D model for the investigation of the biomechanical behaviour of complex structures using the finite element method (FEM), relies on many factors such as: The complexity of the geometry, mode of analysis, the required accuracy; the applicability of general findings and the required time for analysis (Poiate et al., 2011). The 2D model is the most commonly employed by many researchers because of its simplicity, time and cost effectiveness. It requires a relatively normal computer to run the analysis comparing with the 3D model.

For model creation, some researchers in the dental field use computerised tomography scanning data, whilst others depend on the averaged tooth dimensions obtained from the literature to develop a model (Romeed et al., 2006; Magne, 2007; Tajima et al., 2009).

For the purpose of analysing stress using FEA, some essential information is needed such as geometric shape, the material properties which include Young's modulus and Poisson's ratio, in addition to identifying the total number of nodal points and total number of elements, type of boundary constraint etc. Once this information is specified the stress generated can be investigated through specific finite element computer programme (Selna et al., 1975). The analysis can demonstrate internal stresses by which the failure mode can be predicted. Finite element modelling is extensively used by many researchers to analyse the polymerization shrinkage and stress pattern which could initially determine the area where a restoration is likely to fail.

Shrinkage stresses that occurs during the curing process of resin composite materials have been widely studied using the finite element method considering different variables. FEM has been used to simulate the polymerization process (Barink et al., 2003), assess stress distribution and its effect on cuspal movement and tooth deformation (Ausiello et al., 2001; Versluis et al., 2004). The development of stresses at tooth-restoration interfaces in terms of its geometry, thickness and type of material (Ausiello et al., 2002; Ding et al., 2009; Coelho et al., 2008; Ensaff et al., 2001) were also studied using this method. The C-factor and its effect on the stress peak (Rodrigues et al., 2012), use of resin composite Class II inlay restorations (Ausiello et al., 2004) and many other variables were considered using FEA, etc.

Winkler et al. (1996) used the FEM to compare the effect of using three different filling techniques (bulk, horizontal increments and three wedge increments) on

transient stresses generated at the resin composite /tooth interface in a class V cavity preparation during polymerization. They found that the transient stress generated from the bulk filling technique is lower than that of incremental filling accordingly they suggested using bulk filling with a shallow restorations and incremental filling with a deep restorations.

Versluis et al. (1998) studied the direction of composite shrinkage after curing using FEA. They concluded that there was no significant influence of the orientation of the incoming curing light on the shrinkage direction. Otherwise, it may be determined by quality of bonding and the free surfaces.

Ensaf et al. (2001) has examined the interfacial stress around the margins of resin composite restorations using the FEA on 3D half idealised models of tooth structures. They found that the area of the maximum stress is located at the restoration-tooth interface area. They confirmed the role that the lining material has in relieving stresses associated with the polymerisation shrinkage of resin composite materials.

Ausiello et al. (2002) employed FEA to determine the effect of the adhesive layer thickness on the stress relief using 3D models of upper premolar teeth with MOD restorations. They concluded that the intensity of the stresses generated as a result of polymerisation shrinkage of composite restoration, can be limited by using a thicker adhesive layer to absorb material deformation and provide more uniform stress distribution. However, a thick layer does not comply with the manufacturer instruction for use.

Different application techniques using resin composite restoration were studied using 3D FE model of upper premolar teeth with MOD resin composite restorations. Insignificant differences in stress developed at the tooth-restoration interface were found between bulk and layering restoration techniques (Kuijs et al., 2003). Another FEA study by Kowalczyk (2009) considered the effect of the shape of the layer on the shrinkage stress peaks simulating class I resin composite restorations of premolar teeth. They found that the application of a thin pre-layer of resin composite with the rounded layer or wedged technique are likely to give a highest stress reduction.

2.8 Summary

Multiple factors have been shown to effect microleakage of resin composite restorations. These include, polymerization shrinkage, curing variables, application technique, geometry of the cavity preparation, position of the tooth preparation margin, adhesive composition (filled versus unfilled), and the thickness of the adhesive layer. The multiplicity of factors influencing microleakage has led to microleakage studies being difficult and complex. It is difficult to investigate for one variable, whilst controlling for the others. Most of the studies tended to look at each factor in isolation which makes comparison with other studies problematic.

Microleakage assessment techniques employed different materials; however the dye penetration test is considered to be one of the most widely used methods, due to its ease of implementation. In order to assess the dye

penetration score and extension, different tools were employed. Micro CT was one of these tools; it has the advantage of being a non-destructive and provides a large range of information when compared with the commonly used traditional sectioning technique.

Thermocycling which used with the vast majority of microleakage studies is still debatable as some support its use and others considered it un-necessary in terms of validity and clinical significance. This technique on its own includes many variables which can affect the final result results. These variables include range of temperature extremes, transfer times between baths, number of cycles and dwell time.

Finite element analysis is one of the most popular numerical methods used to assess the distribution of the stress and identify the failure mechanisms of resin based restorations. This technique has shown great ability to simulate more complex geometry and provide greater insight into internal stresses of both tooth and restorations.

Polymerisation shrinkage stress generated especially with proximal resin composite restoration with the margin below the CEJ is still considered as a fundamental cause of marginal failure and a subject of concern and attention for the vast majority of the current research. The main focus of the conducted research in this field is to improve marginal seal and prevent early failure of the resin composite restorations.

Based on the previous literature search the co-curing technique was claimed to have clear effect on reducing polymerisation shrinkage stress of resin composite restoration as stated by Knight (1994, 2006).The use of the adhesive system before the application of the RMGIC has shown to increase its bond strength to dentine when compared with polyacrylic acid conditioner (Pereira et al., 1998; Besnault et al., 2004; Geerts et al., 2010; Dursun and Attal, 2011; Poggio et al., 2014) and the use of the low viscosity resin after the application of the adhesive layer has an advantage of absorbing a part of the polymerisation shrinkage stress (Abdalla, 2010). In other words the low shrinkage and low rigidity materials combined together result in less damage to the interface (Labella et al., 1999).

There is no information in the literature about stress distribution with the use of resin composite sandwich restorations when a co-curing protocol is employed and also the extent to which that stress could result in gap formation and microleakage. The previous research conducted to assess polymerisation stress generated with resin composite restorations were mainly using a flat dentine surface as a bonding substrate, which is far different from the same stress generated on three-dimensional tooth preparations (Braga et al., 2006).

Chapter 3:
Fundamental preparation for the in-vitro study (initial steps)

3.1 Introduction

As this study included two parts; Experimental and Finite Element Analysis, the preliminary preparation for the study was divided into two stages; the first stage was to prepare for the experimental work which included teeth collection, obtaining the ethical approval and all the preparation of the samples before starting the experimental work. The second stage was to develop a tooth model to accomplish the finite element analysis and gathering the physical materials properties for both the restorations and the tooth structure. Only the preliminary preparation steps which were required to begin the in-vitro investigations are presented in this chapter.

3.2 Preparation for the in vitro study

3.2.1 Sample size calculation from the pilot study:

Sample size calculation plays an important role at the planning stage to confirm that there are sufficient numbers of subjects to provide for an accurate and reliable assessment of the investigated subjects. It may be performed based on precision analysis, power analysis, probability assessment, or other statistical inferences (Chow et al., 2003).

A review of the literature in the same field of the applied study can provide guidance about “typical” sample sizes which can be used. This is one of the methods used to determine sample size, in which the researchers use the same sample size as those of studies similar to the planned study. Another method is by pre-study power analysis which is probably the most commonly used method for sample size calculation. However, unless there is a formal calculation of the sample size it is not possible to decide whether the previously used sample size truly gives the proposed power or not.

To determine the sample size for this study, a review of the literature was conducted to review the procedures employed not only to determine the sample size used in previous studies but also to avoid the risk of repeating errors that were made in determining the sample size for previous studies.

From the reviewed literature of the same subject and similar investigations, the most commonly used sample size in previous studies (similar to the current one) was 10, 11 or 12 per group. To get a more accurate result, and to compensate for mistakes or fracture during preparation this study used a sample size of 16 per group (32 in total).

On completion of the experiment, the power for study was calculated retrospectively. The result of this study was used in the calculation of the odd ratio, which was needed to find the power of the study.

A retrospective calculation of the sample size needed for this kind of study may reveal how appropriate the previously used sample size was. Moreover, it may help in avoiding the risk of having the same errors in the future studies as underpowered sample sizes might distort the validity and integrity of the intended investigations.

To establish an accurate and reliable sample size calculation, it is necessary to identify the appropriate statistical test for the hypothesis of interest under the study design. The proposed statistical test for the current study was Mann-Whitney U-test which is recommended to be used where the outcome measure of interest for the undertaken study is an ordered scale (variable) in which one subject can be described as being in a higher (or lower) category than another (Machin et al., 1997).

From a previously conducted pilot study, a retrospective power calculation was established and a sample size was calculated.

3.2.2 Retrospective power calculation

The first requirement is to use the odds ratio (OR), which defined as the ratio of odds of having the target disorder in the experimental group relative to the odds in favour of having the target disorder in the control group.

The odds ratio could be anticipated by the experimenter in the instances of new therapy or the experimenter may know the proportions for one group.

Another way of determining the odds ratio is to follow an equation (Machin et al., 1997).

$OR_1 = Qs_1 (1- Q_{T1}) / Q_{T1} (1- Qs_1)$

$= 2/ 16 (1-1/ 16) / 1/ 16 (1-2/ 16)$

$OR_1 = 15/7$

$m = 6(Z_{1-\alpha/2} + Z_{1-\beta})^2 / (\text{Log } OR)^2$

$16 = 6(Z_{1-\alpha/2} + Z_{1-\beta})^2 / (\text{Log } 15/7)^2$

$(Z_{1-\alpha/2} + Z_{1-\beta})^2 = 16 (\text{Log } 15/7)^2 / 6$

$Z_{1-\alpha/2} + Z_{1-\beta} = \sqrt{16(log\ 15/7)^2 / 6}$

$Z_{1-\alpha/2} + Z_{1-\beta} = 1.5$

Table 3.1: Explanation of the Symbol in the equations

OR_1	Odd ratio of having score 1
Qs_1	Proportion having score 1 following separate curing
Q_{T1}	Proportion having score 1 following together curing
$Z_{1-\alpha/2} + Z_{1-\beta}$	Value that can be obtained from certain table at α=0.05 for the current study
M	The sample size per group

Table 3.2: Table generated via SPSS to determine the values of Qs_1 and Q_{T1}

		Score of microleakage				
		Dye penetration that extended up to 1/3 of the preparation depth (score 1)	Dye penetration greater than 1/3, up to 2/3 of the preparation depth (score 2)	Dye penetration extending to the axial wall (score 3)	Dye penetration past the axial (score 4)	Total
Mode of curing	Separately	1	1	11	3	16
	Together	2	1	13	0	16
Total		3	2	24	3	32

Using table 2.3 (Machin et al., 1997) by using the value of (Z1-α/2 +Z1-β), it can be found that the power for the current pilot study was about 30%.

Using table 3.3 (Machin et al., 1997) and by looking for the odds ratio which was calculated from the previous equation the sample size needed to achieve a power of 80% was 39 per group, while for a power of 90% the number per group was 52.

It was decided to use the power of 90% for the current study requiring a sample size of 52 restorations per group a total of 104 restorations.

3.2.3 Sample collection

Freshly extracted premolar teeth were collected from Leeds Dental Institute tissue bank. Due to initial difficulties in accessing sufficient numbers of freshly

extracted teeth, an application to start collecting sound freshly extracted premolar teeth was submitted to the tissue bank at Leeds Dental Institute. The application was approved and tooth collection was carried out. However, it was found that the number of available teeth was very low.

Following difficulties in accessing sufficient teeth from the Dental Institute, an application was made to the Local Research Ethical Committee, (Yorkshire & the Humber Leeds Central) to obtain ethical approval to start collecting the required number of teeth for the experimental work from four General Dental Practices. The documentation for the application included; two patient information sheets, one for children aged 12-17 (Appendix A.1) and other one for adults (Appendix A.3); an assent and consent forms (Appendix A.2, A.4). The application was approved (Appendix A.5) and the collection of the teeth commenced, after the tissue transfer agreement was signed by the dentists contributing to the study (Appendix A.6).

3.2.4 Sample selection and storage medium

Extracted teeth were cleaned and any adherent hard and soft tissues deposits were removed using periodontal hand scalers (refinement scaler, Dentsply). The teeth were initially stored in a 0.5% chloramine solution (Chloramine T GPR, VWR International, Lutterworth, Leicester, UK) for a maximum of one week and thereafter in distilled water in a refrigerator at a nominal $4^{o}C$ until the commencement of the experiment. These procedures were in accordance with

the recommendations of the International Organization for Standardization (ISO, 2003).

Subsequently, the teeth were trans-illuminated and visually inspected to detect any cracks, fracture, defect and caries. Any teeth found to include any significant defects, or other abnormalities were excluded from this experiment; in order to avoid unwanted ingress of dye material during the microleakage test.

Chapter 4

Preliminary investigation

4.1 Pilot study (Preliminary investigation)

A pilot study was conducted to assess the feasibility of the experiment and develop methodology for the main study. This pilot study was a preliminary investigation to develop a protocol for the restoration.

Freshly extracted premolar teeth were collected from Leeds Dental Institute tissue bank. Due to initial difficulties in accessing sufficient numbers of freshly extracted teeth, four preparations per tooth were prepared in order to obtain the proposed sample size and reduce the number of the teeth required for the experiment, Seven premolar teeth were collected and included in the pilot study.

The teeth were prepared according to the method described in Chapter 3.

4.2 Experimental design:

The study design was an in-vitro investigation of open-sandwich restorations using two different curing protocols

- The conventional protocol: in which the resin modified glass ionomer (the base) was cured first and then the first layer of the resin composite was applied and cured;

- The co-curing protocol: in which the two materials were cured together (resin modified glass ionomer and resin composite).

4.2.1 For the control group:

Open sandwich restorations were placed using light cured resin modified glass ionomer cement (base) and resin composite (main restoration). A conventional protocol, for curing using halogen light curing unit, was followed by fully curing the RMGIC for 20 seconds prior to the additional incremental curing of the resin composite for 40 seconds for each layer.

4.2.2 For the test group:

Open sandwich restorations were placed using light cured resin modified glass ionomer cement (base) and resin composite (main restoration). In contrast to the control group the two materials were light cured simultaneously for 40 seconds.

4.3 Sample allocation:

No randomization was needed as both the test and control groups were placed in the same tooth. A consistent order was followed by considering both the buccal and mesial surfaces of the tooth to have the separate curing protocols while lingual and distal surfaces to have the co-curing protocol.

4.4 Teeth mounting

All teeth included in the experiment for this study were mounted in maxillary and mandibular Columbia rubber moulds (Novo dental products Pvt.Ltd. RM-22 for 32 teeth). In each case the test tooth was located in the mould between two Typodont plastic teeth to simulate the clinical situation in order to establish appropriate anatomical relationships and contact points Fig (4.1).

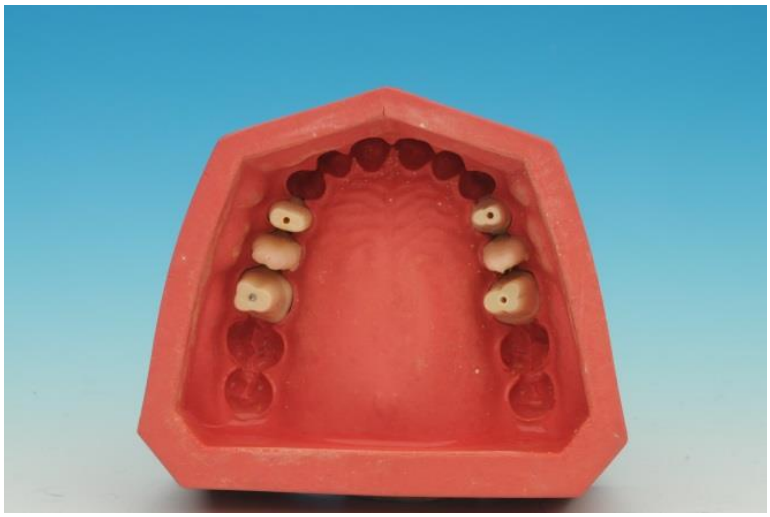


Figure 4.1: Columbia mould with natural second premolar tooth in between two Typodont teeth (first premolar and first molar).

The mould was poured using dental plaster (Crystacal D stone; BPB Formula, Nottinghamshire, England) and then allowed to completely set fig (4.2). Subsequently, the casts including the mounted teeth were covered with wet gauze to keep the teeth hydrated all the times. The specimens were then stored in plastic bags and care was taken to ensure that the models did not dry out.

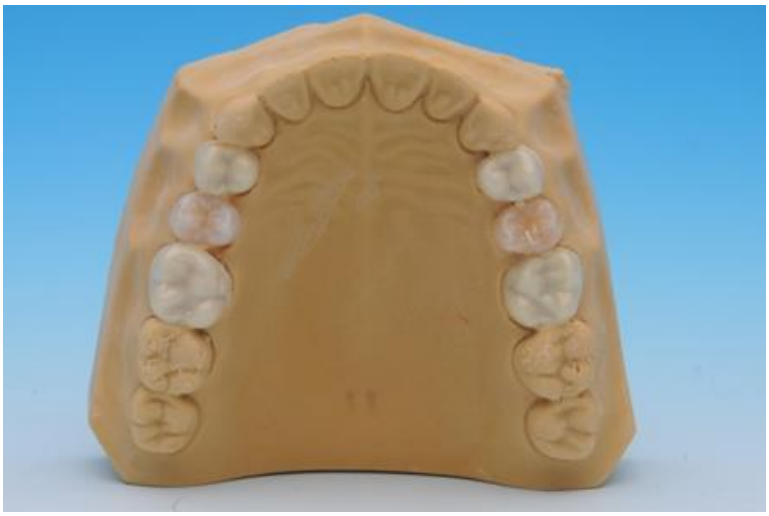


Figure 4.2: Cast with the mounted teeth

4.5 Preparation of the cavities

Four slots were prepared on each tooth on mesial, distal, buccal and lingual surfaces. All the slots were prepared by the chief investigator to ensure a standardised cavity preparation**.**

4.6 The features of the preparation

The slots were prepared as follows:

- A bucco-palatal / bucco-lingual width of 3.0 mm for both mesial and distal preparations.
- A mesio-distal width of 3.0 mm for both buccal and lingual preparation
- A cervical wall width of about 2 mm.
- Pulpal wall was parallel to the long axis of the tooth.
- The gingival cavosurface margins were located 1 mm below the cement-enamel junction (CEJ).

All the preparations were standardised by using fine-pointed water proof pen (Lumocolor, Staedtler, Germany) to mark the occlusal outline of the preparation which was determined using a periodontal probe (Michigan O probe with Williams markings which has circumferential lines at 1, 2, 3, 5, 7, 8 , 9, and 10 mm). The length needed to place the gingival margin entirely apical to the CEJ was different amongst teeth and dependent on the anatomy of the individual tooth. A reduction of the buccal and lingual cusp tips was made in order to match the height of the mesial and distal surfaces.

All of the slots were prepared in each tooth using a water-cooled diamond bur held in a high speed handpiece (KAVO Dental Excellence, Biberach, Germany). A new cutting bur was used after the preparation of every five cavities.

To ensure consistency in preparation size a check was performed on each preparation using a periodontal probe to determine if any inaccuracy in the dimensions of the preparation had occurred. Any faulty preparations were discarded and replaced.

After finishing the preparations, the plaster casts including the prepared teeth were covered with wet gauze and inserted in plastic sealed bags and stored at room temperature (20◦ C).

Using the water proof pen, marks were then placed on the cast to determine the control and test preparations.

4.7 Materials and instruments used during restorations and finishing:

1. The resin composite used in the study was an injectable micro-hybrid light-cured resin composite (XRV Herculite; Kerr U.K. Ltd), which contains approximately 79% by weight (59% by volume) inorganic filler with an average particle size of 0.6 microns. Shade A3 was used.
2. A radiopaque light cured resin modified glass ionomer cement (GC Fuji II LC, GC Corporation, Japan) (Shade A3).
3. 37% phosphoric acid (Super etch, Southern Dental Industries, Australia).
4. Dentine adhesive system (OptiBond Solo Plus, Kerr, USA).
5. Sectional matrices (Palodent® sectional matrix system, Dentsply) (Figure 4.3).
6. Wooden wedges (Wizard wedges; Teledyne Dental, Bremen, Germany).
7. Curing light unit (QHL75® Lite, Dentsply) with an output of 400 mw/cm².
8. Curing radiometer (Demetron research corporation, Danbury, USA) .
9. Finishing strips.
10. soflex discs which ranged from coarse, medium and fine (3M Sof-Lex™; 3M ESPE, St. Paul, MN)
11. White and green stone, finishing burs.

Table 4.1: Manufacturer instruction for use for the materials used in the study

Materials	Manufacturers' instructions	Batch Number
37% phosphoric acid etchant	1.Etch enamel and dentin for 15 seconds 2. Rinse thoroughly, ensuring that all etch is removed. 3. Dry lightly, do not desiccate.	120648
OptiBond Solo Plus	1.Apply to enamel/dentine surface with applicator tip for 15 seconds, using light brushing motion. 2.Air thin for 3 seconds. 3.Light cure for 20 seconds.	4785282
GC Fuji II LC (resin modified glass ionomer cement)	1.Mixing time 10 seconds. 2.Working time 3 minute and 15 seconds. 3.Light curing time 20 seconds. 4.Depth of cure 1.8 mm. 5.Extrude cement directly into preparation avoid air bubbles. 6.Place light source as close as possible to the cement surface.	1210225
Micro-hybrid light-cured composite (XRV Herculite) Unidose delivery.	1.Insert Unidose tip and properly align within Dispenser. 2.Place the Unidose tip at the deepest portion of the preparation. Caution: extrude slowly with even pressure. 3.Increments should be no more than 2mm at a time. 4.After placing an increment stroke the composite to ensure marginal adaptation. 5.Light cure each increment for 40 seconds.	4668053

4.8 Restoration technique:

4.8.1 Treatment common to both groups

A sectional matrix band (Palodent system, Dentsply) was placed around each prepared tooth on both mesial and distal slots and further adapted using wooden wedges (Wizard wedges; Teledyne Dental, Bremen, Germany). A spring ring was then placed using ring placement forceps (Palodent system, Dentsply).

Figure 4.3: Palodent matrix bands system

All the preparations were etched with 37% phosphoric acid (Super etch, Southern Dental Industries, Australia) according to the manufacturer's directions of use (Table 4.1). The etchant was placed on the preparation's walls for 15 seconds. The preparations were then washed thoroughly with water and then lightly dried using a soft blow of oil-free compressed air. Subsequently the etched surfaces were coated with adhesive (OptiBond Solo Plus, Kerr, USA) which was then air thinned for 3 seconds, and light cured for 20 seconds in accordance with the manufacturer instructions table (4.1).

All of the etching and adhesive applications was accomplished after placement of the matrix band.

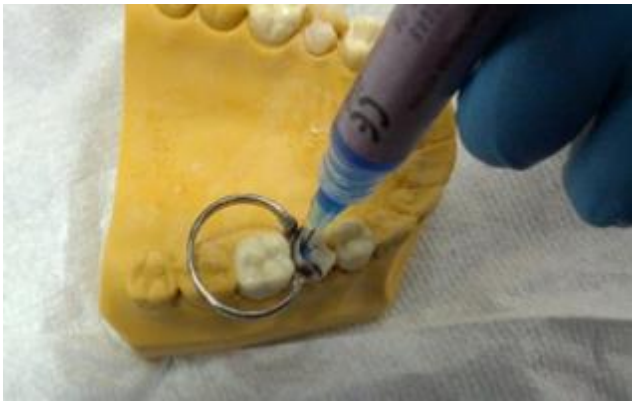


Figure 4.4: Acid etching

GC Fuji II capsule was loaded into the GC capsule applier; an increment of about 1mm thickness of the GC Fuji II was injected directly into the preparation. After that, each group was cured in a different manner as specified below. The intensity of the curing light (halogen curing light unit) was checked prior to each use with a radiometer (Demetron research corporation, Danbury, USA) to deliver 400 Mw/cm^2.

4.8.2 Treatment specific to each group

4.8.2.1 Control group

The RMGIC increment was light cured for 20 seconds, and subsequently resin composite was then injected incrementally into the remaining part of the preparation following the manufacturer's direction for use table (1.4). Each increment was less than 2 mm thick and was carefully adapted by applying light pressure using hand instruments, and light cured for 40 seconds.

4.8.2.2 Test group

The same technique as that of the control group was employed for this group except that the layer of the RMGIC and the first increment of composite were cured simultaneously.

The final layer of resin composite was carefully placed and sculpted before curing.

The matrix band and wooden wedge were then removed and the restorations were then finished occlusally using the green and white stone finishing burs held in a slow speed hand-piece. Proximally the restorations were finished using finishing strips, and a series of soflex discs which ranged from coarse, medium and fine (3M Sof-Lex^{TM}; 3M ESPE, St. Paul, MN, USA). Subsequently, the teeth were carefully removed from the casts, a small dot was then prepared on the end of the root to define the control restorations and kept wet using water soaked gauze and stored in plastic storage bags at room temperature (20º C).

4.9 Specimens ageing

All teeth were placed in the Thermocycling apparatus at the University of Manchester, School of Dentistry, Biomaterial Science Lab and subjected to 500 cycles. The temperature of the baths was maintained at 5 ± 2 ^{o}C and 55± 2 ^{o}C. The teeth were left for 15 seconds dwell time in each bath and approximately 10s to transfer from one bath to another following the ISO standard (ISO, 2003). Following this, the teeth were returned to the plastic bag and kept wet using water soaked gauze at room temperature (20º C).

Figure 4.5: Thermocycling machine

4.10 Microleakage investigation:

Following Thermocycling, specimens were prepared for microleakage testing.

Before immersing the teeth in dye solution the root apices were sealed with sticky wax to prevent unwanted ingress of tracer, and then two layers of nail varnish were applied to additionally seal the apex and tooth surfaces. Care was taken not to cover the restoration itself and to be within 1mm of the tooth-restoration interface.

The restored teeth were immersed in 50% silver nitrate solution for 4 hours at room temperature (20º C). The teeth were placed in a UV light box in a small container filled with 1:9 developer solutions (ILFORD ILFOSOLS.10 ml of the solution mixed with 90 ml of distilled water) for 6 hours. After this, teeth were

rinsed under running water. Each tooth was then wrapped with wet tissue and inserted in a small plastic pot covered with a secured lid.

Two techniques were used in order to investigate the microleakage and the level of the dye penetration.

- The first technique was by scanning the teeth using the **x- ray micro computed tomography**.
- The second technique was by **sectioning the teeth**.

4.11 X-ray Micro Computed Tomography (Micro CT):

Micro Computed Tomography (Scanco medical100) was used to scan the teeth by mounting the specimen into the Micro CT cylindrical holder.

The plastic pot was placed in a cylindrical holder size 34mm× H 110 mm and secured in place by using small pieces of foam sponges. Once the tooth was secured in place the cylinder was mounted into the machine and the carousel number noted, the area for scanning was selected using a scout scan. The x-ray setting was (90 kvp, 14 W) with high resolution of 17.2 µm, using the 0.5 aluminium filter. Once the adjustment for the scanner was finalized the scanning procedure was started. The raw data were then generated and further reconstructed and converted to 16-bit-mapped images files showing 2D images. Images were then analysed using public domain software; image J (imaging processing and analysis in Java) by using the orthogonal views (Fig 4.6, 4.7, 4.8, and 4.9). In those views the restoration appeared to be radio-opaque and air gaps and adhesive were radiolucent.

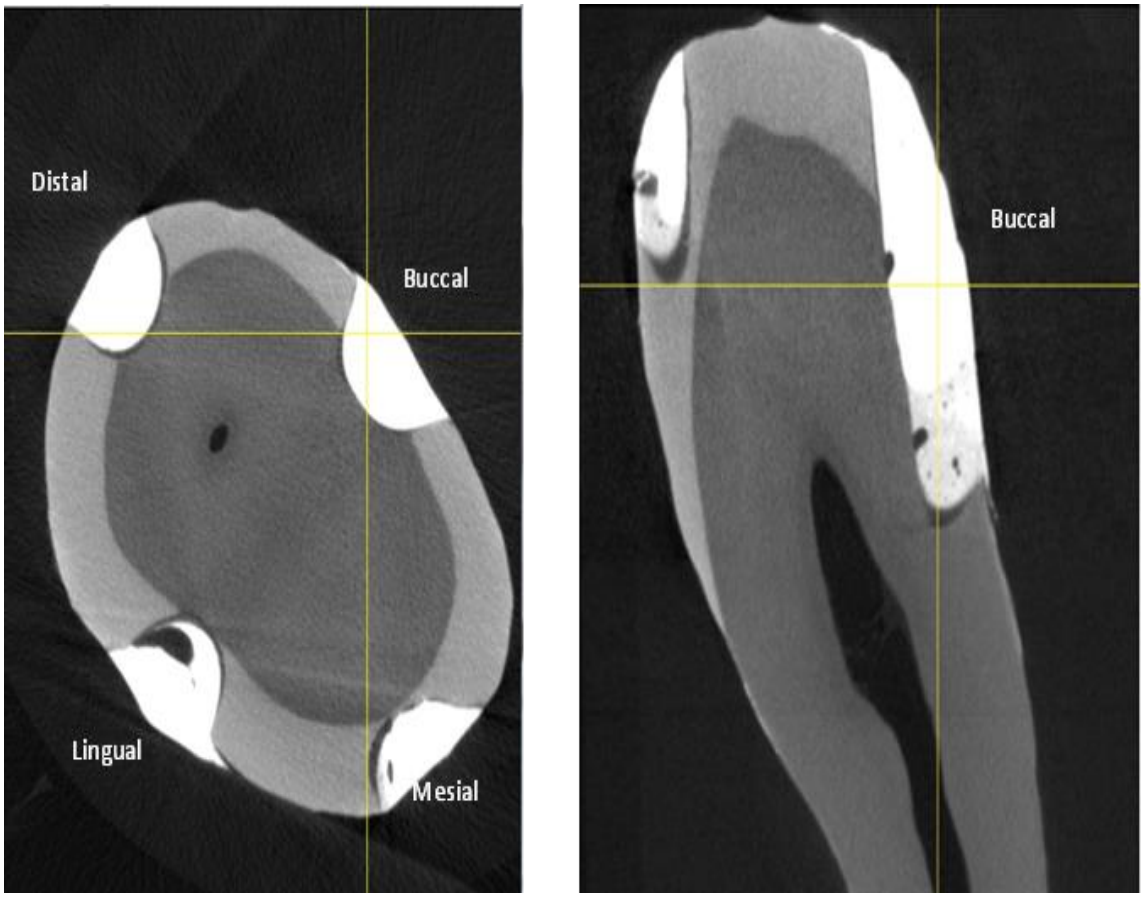


Figure 4.6: Orthogonal view of the buccal restoration

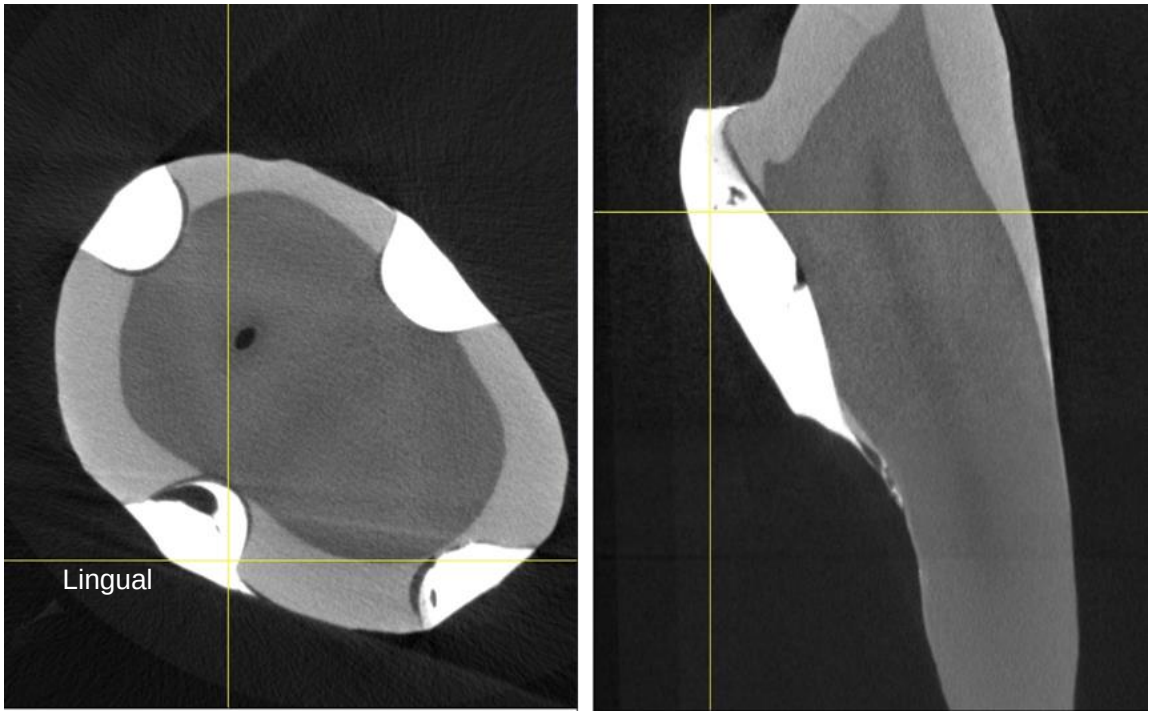


Figure 4.7: Orthogonal view of the lingual restoration

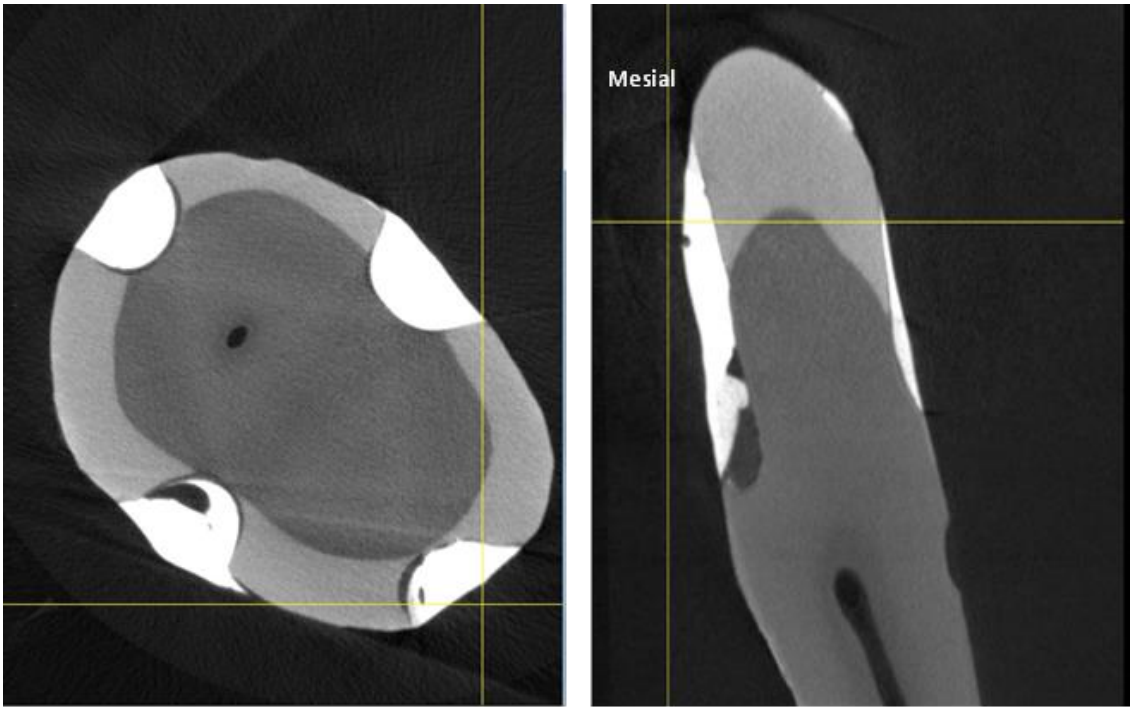


Figure 4.8: Orthogonal view of the mesial restoration

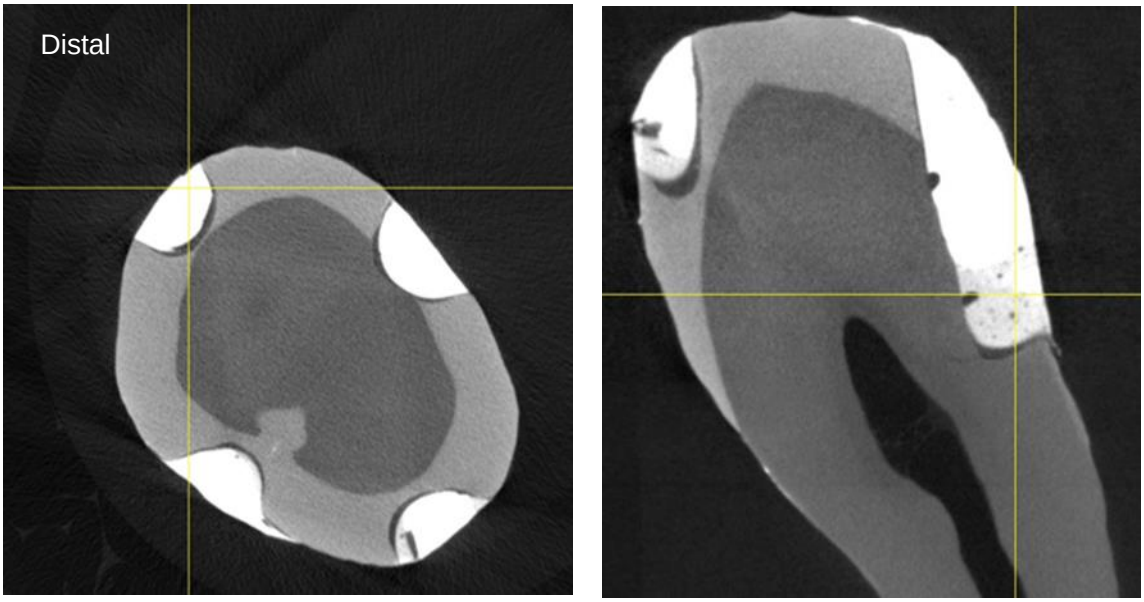


Figure 4.9: Orthogonal view of the distal restoration

4.11.1 Results from the Micro CT scanning image:

From the 2D orthogonal view generated via Image J (as in Figures 4.6, 4.7, 4.8, and 4.9) the main findings were

1. Air gaps in the restoration.

2. Space left between the resin composite restoration layers.

3. Adhesive layer which can be identified by its radiolucent (black) colour.

4. Overhanging restoration

5. Silver nitrate penetration was not recognized.

4.12 Sectioning technique:

Each tooth was embedded in place on a round plastic disc using warmed green stick compound (Fig 4.10.). The plastic disc was then tightly screwed on the sectioning machine (precision diamond wire saw with constant water coolant) (Fig 4.11).

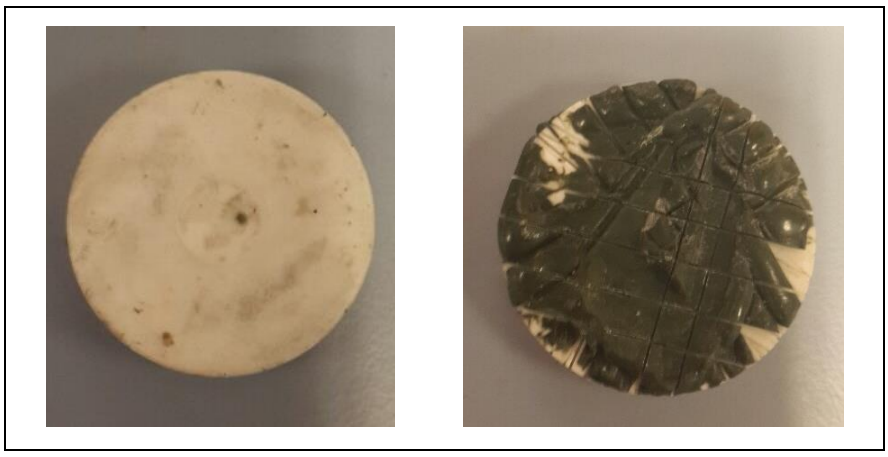


Figure 4.10: Plastic disc with the green compound

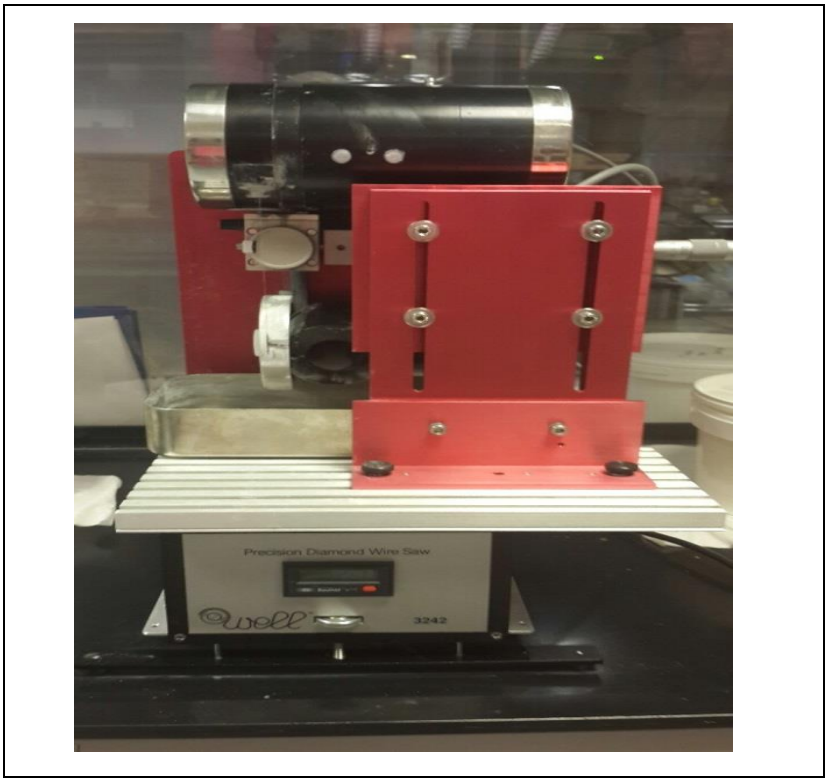


Figure 4.11: Sectioning machine

The teeth were sectioned twice mesio-distally using a slow-speed diamond wire saw under copious water coolant. The buccal and lingual (palatal) restorations were then sectioned separately bucco-lingually (palatally) two sections each. The two sections provided four surfaces to score in each restoration (Fig 4.12).

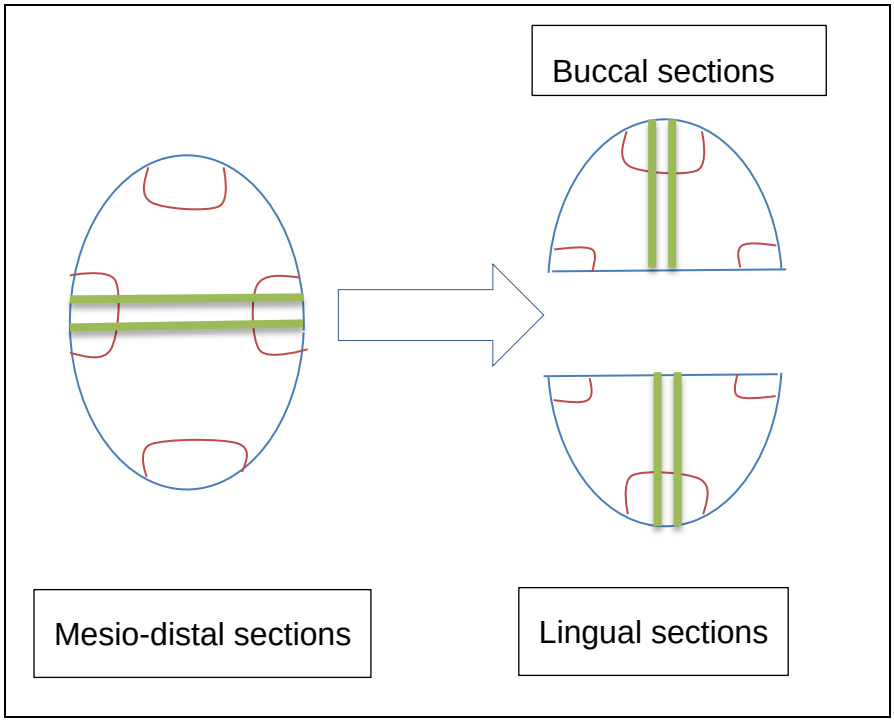


Figure 4.12: Sectioning technique

Each specimen was then examined under a stereo zoom microscope at x20 magnification to be scored using a protocol described by (Gharizadeh et al., 2007). The assessment of the microleakage scores was based on the depth of the dye penetration, according to the following ordinal 5 point scale from 0 to 4 (Fig 4.13).

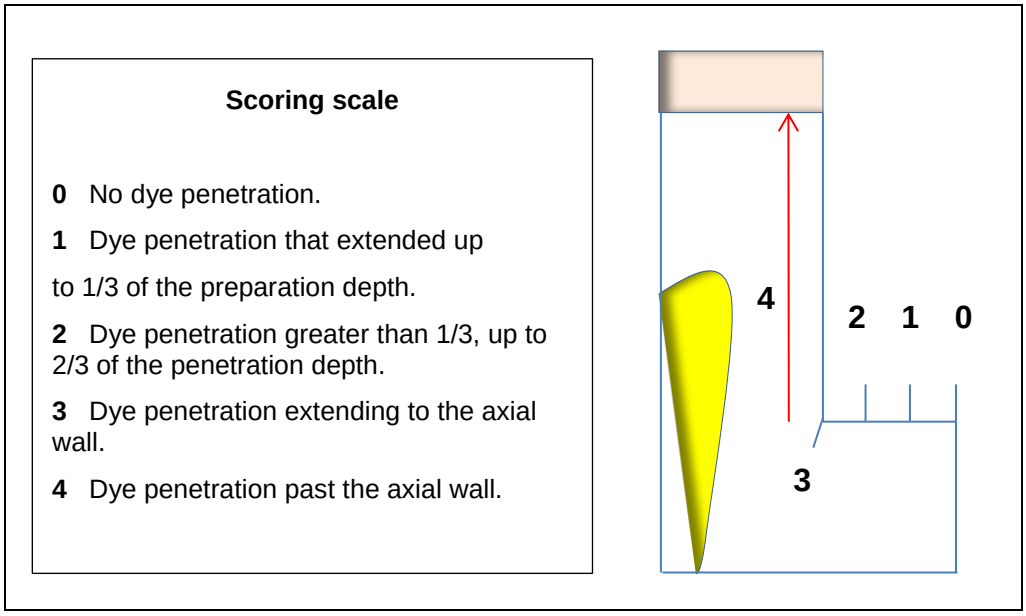


Figure 4.13: Dye penetration scoring scale

4.12.1 Sectioning technique result:

As can be seen from the Table (4.2) most of the restorations were leaking to the highest score (score 4), only one of the restoration showed no leakage (zero score), in which the restoration showed an overhanging margin which could have prevented the dye from penetration.

Table 4.2: Microleakge scores from sectioning technique.

Tooth Number	Surface	Sections	Microleakage score	Highest score
1	Buccal	1	4	4
		2	4	
		3	4	
		4	4	
	Lingual	1	4	4
		2	4	
		3	4	
		4	4	
	Mesial	1	4	4

		2	4	
		3	4	
		4	4	
	Distal	1	4	4
		2	3	
		3	Out	
		4	Out	
2	Buccal	1	4	4
		2	4	
		3	4	
		4	4	
	Lingual	1	Out	4
		2	4	
		3	4	
		4	4	
	Mesial	1	4	4
		2	3	
		3	3	
		4	2	
	Distal	1	4	4
		2	4	
		3	Out	
		4	Out	
		2	4	
		3	4	
		4	Out	
3	Buccal	1	4	4
		2	4	
		3	4	
		4	Out	
	Lingual	1	4	4
		2	4	
		3	4	
		4	Out	
	Mesial	1	3	4
		2	3	
		3	3	
		4	4	

	Distal	1	0	0
		2	0	
		3	0	
		4	0	
4	Buccal	1	Out	4
		2	4	
		3	4	
		4	4	
	Lingual	1	4	4
		2	4	
		3	4	
		4	4	
	Mesial	1	4	4
		2	4	
		3	4	
		4	4	
	Distal	1	4	4
		2	4	
		3	4	
		4	Out	
5	Buccal	1	4	4
		2	4	
		3	4	
		4	4	
	Lingual	1	4	4
		2	4	
		3	4	
		4	4	
	Mesial	1	4	4
		2	4	
		3	4	
		4	4	
	Distal	1	4	4
		2	4	
		3	4	
		4	4	
6	Buccal	1	3	3
		2	3	

		3	3	
		4	3	
	Lingual	1	4	4
		2	4	
		3	4	
		4	4	
	Mesial	1	4	4
		2	4	
		3	4	
		4	4	
	Distal	1	3	4
		2	3	
		3	4	
		4	4	
7	Buccal	1	4	4
		2	4	
		3	4	
		4	4	
	Lingual	1	4	4
		2	4	
		3	4	
		4	4	
	Mesial	1	3	3
		2	3	
		3	3	
		4	3	
	Distal	1	4	4
		2	4	
		3	4	
		4	4	

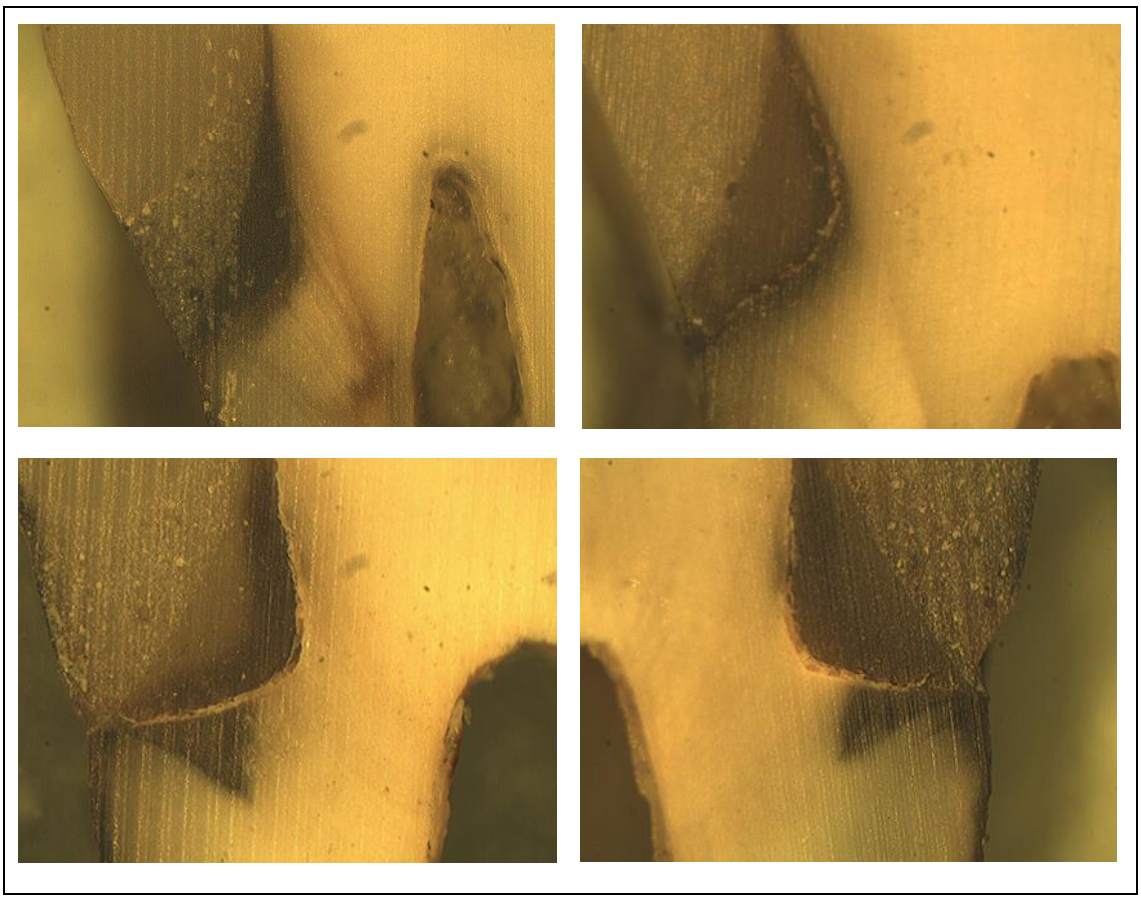


Figure 4.14: Stereomicroscope image showing dye penetration

Figure (4.14) showed the highest microleakage score of score 4 which was found on the vast majority of the samples. One of the sample showed no dye penetration of score 0 (Fig 4.15).

Adhesive pooling in cervico-axial angle in the floor of the restoration was a common phenomenon in almost all the samples.

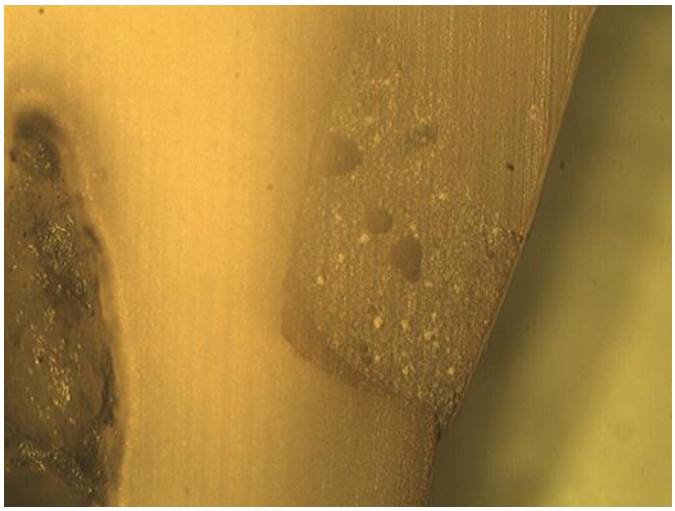


Figure 4.15: stereomicroscope image for no dye penetration

4.13 Discussions:

4.13.1 Number of the preparations per tooth

After performing the initial experimental design, it became apparent that four preparations per tooth were not practical, as they were likely to increase the number of mechanical variables therefore affecting the final result.

4.13.2 The use of the matrix band during adhesive application

Certainly in the base of the cavity the adhesive was pooled and created a thick inconsistently distributed layer. The presence of the matrix band during the application of the adhesive may have prevented any excess adhesive from seeping away from the cavity margin especially after the air thinning procedure leading the adhesive to accumulate at the corner of the restoration which is commonly called adhesive pooling. This was in agreement with the finding of the research conducted by (Ernst et al., 2002) who recommended the adhesive be placed prior to the placement of the matrix system in class II cavities owing

to different factors which included: the presence of the matrix band could first impair the insertion of the micro brush applicator into the proximal cavity to apply the adhesive to all the cavity walls and lead to insufficient conditioning, second; make it difficult to air dry the adhesive which is essential to remove the solvent, third; prevent removal of the excess material in the cervical direction resulting in a thick adhesive layer, fourth; adhere strongly to the adhesive material and potentially cause a disruption of the interface upon the matrix removal.

4.13.3 Sectioning technique

During sectioning, the tooth become gradually weaker, very fragile slices were obtained and there was more risk that the interfaces might become contaminated by the sectioning process. The fragility also increased the possibility of restoration fracture and separation from the tooth surface.

4.13.4 Number of sections

A single midline section is the most commonly applied technique for dye penetration assessment. It is however; difficult to represent the total dye distribution through the whole restoration using only one section (Youngson et al., 1998; Federlin et al., 2002). Multiple sections are necessary for the detection of the deepest leakage site at the tooth-restoration interface. Two sections were chosen to avoid underestimation of microleakage (Raskin et al., 2003). The maximum dye penetration scores on each restoration were recorded

as it is the most relevant criterion in evaluating microleakage (Dejou et al., 1996).

4.13.5 Micro CT

Micro.CT is an expensive tool to use and needs specific training and mastery of the image processing software. It has the advantage of being a non-destructive, non-invasive method when compared with the sectioning technique. However, the micro CT technique was not appropriate to use for the purpose of this study owing to the large number of slices generated per tooth and also dye penetration was not clearly defined with this technique.

Moreover the Micro CT scan resulted in about 600 slices which was hard to match with the tooth section from the sectioning technique and resulted in a difficulty in comparing the result from the two techniques. It was also hard to view the full section of the tooth

From the researcher point of view more training was needed in order to be able to acquire a detailed image which would allow for assessment of the total area of the restoration.

4.14 Limitations of the study:

4.14.1 Dye penetration test

Dye penetration testing is widely used to test microleakage (Haller et al., 1993). The wide variety of dye materials used in in-vitro tests of microleakage, results in conflicting findings and difficulty in comparing many of the study outcomes

(Dejou et al., 1996) as they lack standardization of the parameters for comparison. It has been advised, therefore, not to compare the results of microleakage studies that used different tracers (de Almeida et al., 2003).

Silver nitrate was used in this study as it is a metal dye which can be visible when using Micro CT, and it is the most widely used dye in other microleakage studies, although some investigators have shown that the acidic nature (PH of 3.4) of the dye can demineralise dentine and allow for the penetration of the dye even with no gap in the interface which compromises the validity of the result, (Li et al., 2003). Another researcher found that the pH of the tracer has no significant effect on dye penetration when they compared a buffered and a non-buffered solution (Youngson et al., 1998).

4.14.2 Storage media

The effect of the storage media on microleakage must also be considered. Extracted teeth used in the in-vitro studies are usually stored in disinfecting solution during the collection period in order to prevent bacterial colonization (Pagniano et al., 1986). Different storage solutions have been used such as ethanol, formalin, and thymol. It has been reported that they may have an effect on the bond strength to dentine. 1% Chloramine T, has been shown to have no effect on the size of the marginal gap compared with water storage (Jorgensen et al., 1985); it was also reported to allow adhesion comparable to that achievable to freshly extracted teeth (Haller et al., 1993).

4.15 Conclusions

To conclude, the micro CT technique was not suitable to use for the purpose of this study.

Application of the adhesive in the presence of the matrix band was thought to have an effect on the adhesive pooling in the cervico-axial angle of the restoration.

The number of cavities (four cavities per tooth) was not practical in terms of sectioning, examination of the samples and also overstressing the tooth structure.

Some sections were out of the restoration which could affect the overall result.

Accordingly, some modifications for the study protocol were proposed in order to avoid the previously mentioned issues in the main study. The modifications included:

1. The adhesive material should be applied before inserting the matrix band.

2. More attention should be given during the sectioning stage to avoid out of restoration tooth section.

3. No more than two cavities per tooth would be prepared.

Chapter 5

Main study

5.1 Intoduction

Following the findings of the pilot study, the initial study protocl was applied in the main study apart from modified some modifications as described in Chapter 4. These were:

1.Number of cavity preparations in each tooth.

2.Sample randomization.

3.Adhesive placement before applying matrix band.

1.Number of cavity preparations in each tooth

Only two proximal slots per tooth were prepared; one on the mesial surface and the other one on the distal surface; with the same preparation features described in Chapter 4.

2. Sample randomization

Proximal slots were randomized using research randomizer website (*research randomizer*) for both the control and the test group, in which the control group was the separate curing group and the test group was the co–curing (Appendix C.1).

Mesial and distal slot cavities were prepared. Randomization was carried out to determine the order of cavity restoration for the two techniques under

investigation. The second restored slot could potentially be affected by the stresses already generated from the first restoration.This could lead to crack propagation which could cause the second restoration to develop defects unrelated to the technique followed in the restoration.

3.Adhesive application with no matrix band

A matrix band was used in the pilot study and was thought to predispose to adhesive pooling. For the main study the adheisve was applied without placing the matrix band for all the samples.

5.2 Aim:

The aim of this research was to investigate the effect of curing resin modified glass ionomer cement (RMGIC) and resin composite in open sandwich restorations, either together or seapartely on the marginal leakage of the restorations.

5.3 Objective

5.3.1 Dye penetration test

To assess the dye penetration between the tooth and restoration interface using a sectioning technique.

5.4 Investigation of dye penetration:

All of the teeth sections when examined under the stereomicroscope at x20 magnification showed that the dye was absorped by the adhesive and therefore scoring the depth of dye penetration between the restoration and the tooth was not possible. The main finding was that the adhesive thickness appeared to be much greater than anticipated and adhesive pooling was present despite the modification of the methodology to place the adhesive before applying the matrix band.

Ten sections of teeth were then examined under the SEM (Scanning Electron Microscope) in order to examine the restoration/ tooth margin for gap formation.

5.5 Preparation of the sample for the SEM investigation

The surface of the tooth section was polished with 1600-grit Silicon carbide (SiC) paper to smooth the surface and rinsed with water to remove any debris. The specimen was dipped in a 50% (w/v) H_3 PO_4 (phosphoric acid solution for 3 seconds (demineralization step), then immersed in a 1% NaOCl (Sodium hypochlorite) solution for 10 minutes to remove the non-encapsulated collagen fibrils. The specimen was then mounted in the SEM [HITACHI, S-3400N] for high resolution examination, using the wet stage in which the sample was placed on the stage (Deben Ultra Mk3, cool stage) and cooled to -20°C with a pressure of 70 MPa.

5.6 Results of SEM imaging:

The SEM images showed that the tooth restoration interface was intact (Appendix.C). However, failure was detected at the cervico-axial angle of the restoration where the adhesive was at its greatest thickness. The adhesive material exhibited crack formation which was propagated into the resin modified glass ionomer cement as can be seen in Figure 5.1.

A possible explanation for this result may be an adhesive film thickness greater than the 10 µm thickness claimed by the manufacturer to be the optimium required. This increased volume of resin would have had a large volumetric shrinkage generating high stresses within the tooth and restoration.

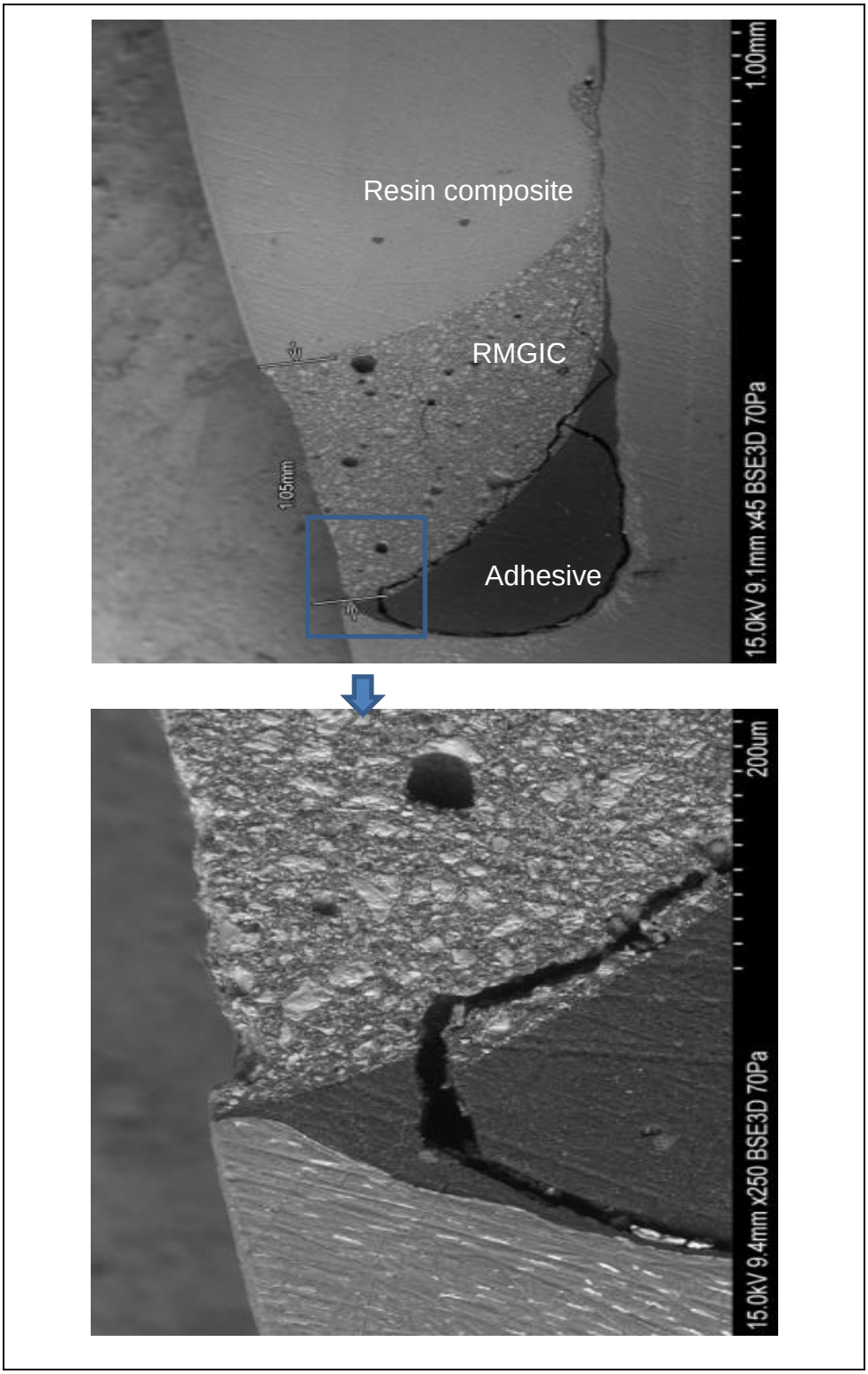


Figure 5.1: Intact margin and crack propagation in the adhesive.

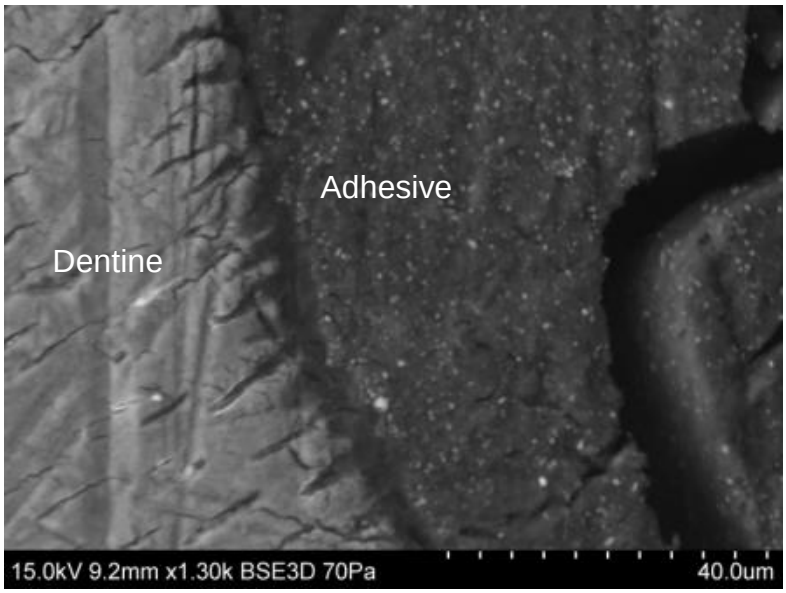


Figure 5.2: Magnified image from SEM of 400 µm

Figure 5.2 has shown a resin tag formation between the adhesive layer and the dentine.

From the SEM results it can be postulated that there were variations in the adhesive thickness from the film thickness of 10 micron claimed by the manufacturer. This could have a significant effect on the stress generated in the tooth and the restoration.

At this stage of the current study it became clear that further investigation was indicated in relation to the increased adhesive thickness and its effect on restoration failure.This was in response to the finding that the adhesive thickness was found to be greater than that anticpated by the manufacturer As the adheisve thickness showed to be greater than that anticpated by the manufacturer.

This increased adhesive thickness was an unanticipated finding and could have had an effect on the marginal integrity of the restoration, leading to failure. It was decided that this aspect required further experimental investigation. The aim of this additional study was to determine whether the thickness of the adhesive showed a large variation within the sample when applied by the main investigator.

5.7 Methods:

The adhesive thickness was measured in all the teeth sections, which had previously been examined for dye penetration. The measurment was accomplished using a photographed tooth section captured using a Motic camera connected to the stereomicroscope. Calibration of the software was made in order to obtain an accurate measurment. A line was drawn through the thickest part of the adhesive (Figure 5.3). The area with the greatest thickness was measured.

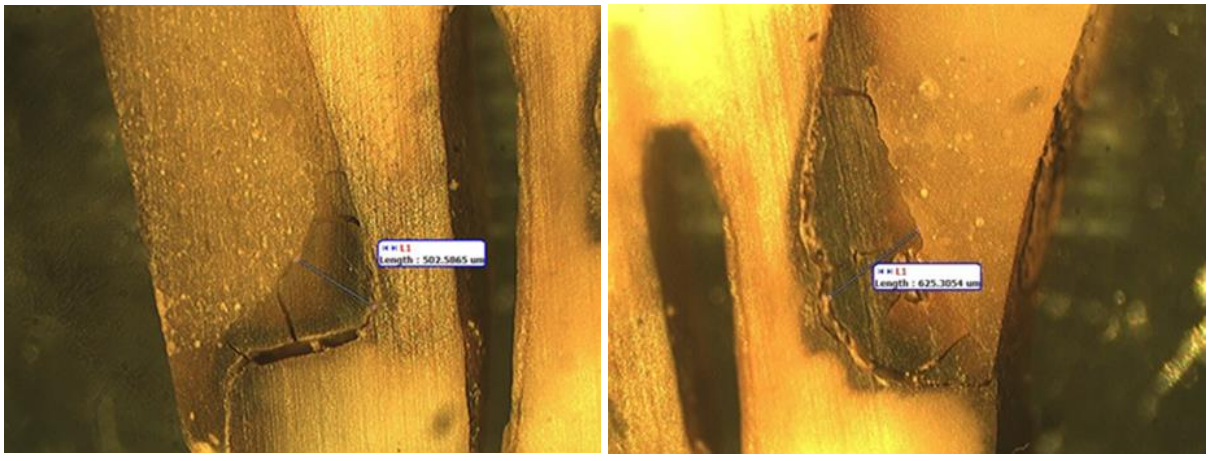


Figure 5.3: adhesive pooling and thickness measurment

Table 5.1: Precured adhesive thickness of all teeth sections

Tooth	**Precured adhesive thickness**	
	Separate curing of RMGIC/RC	Co- curing RMGIC/RC
1	542.96	411.83
2	386.44	593.61
3	95.03	591.34
4	625.31	505.75
5	520.35	602.84
6	306.15	424.33
7	378.28	699.71
8	629.82	503.3
9	454.92	421.69
10	517.47	93.5
11	458.1	306.98
12	930.92	36.55
13	412.8	649.51
14	442.94	175.03
15	445.95	315.8
16	258.78	365.34
17	240.05	303.04
18	502.59	231.86
19	527.6	409.44
20	216.86	434.2
21	639.48	621.96
22	575.28	517.03
23	799.25	291.05
24	600.15	184.56
25	709.95	358.24
26	389.67	74.34
27	317.28	847.24
28	421.84	661.57
29	508.22	646.65
30	636.55	494.71
31	394.35	336.85
32	328.12	879.78
33	518.69	624.01
34	345.78	646.64

35	160.51	243.46
36	411.56	540.76
37	126.67	236.71
38	389.37	680.79
39	495.85	908.06
40	854.18	431.11
41	637.99	538.76
42	615.51	684.13
43	599.05	318.82
44	483.31	571.83
45	344.86	36.86
46	608.83	380.22
47	290.36	421.74
48	735.42	617.98
49	545.29	412.8
50	646.08	638.58
51	472.56	490.73
52	383.08	170.56

The Table 5.1 presented the adhesive thickness measured on a microscopic photograph .

Table 5.2: Descriptive Statistics of all data (separate curing and co-curing group)

	N	Minimum	Maximum	Mean	Std. Deviation
All data (test and control group)	104	36.55	930.92	465.9977	192.47122

5.8 Results:

It is apparent from the Table 5.2 that the thickness of the adhesive ranged between a minimum of 36.55 µm and a maximum of 930.92 µm, the mean layer thickness was 465.9± 192.47µm.

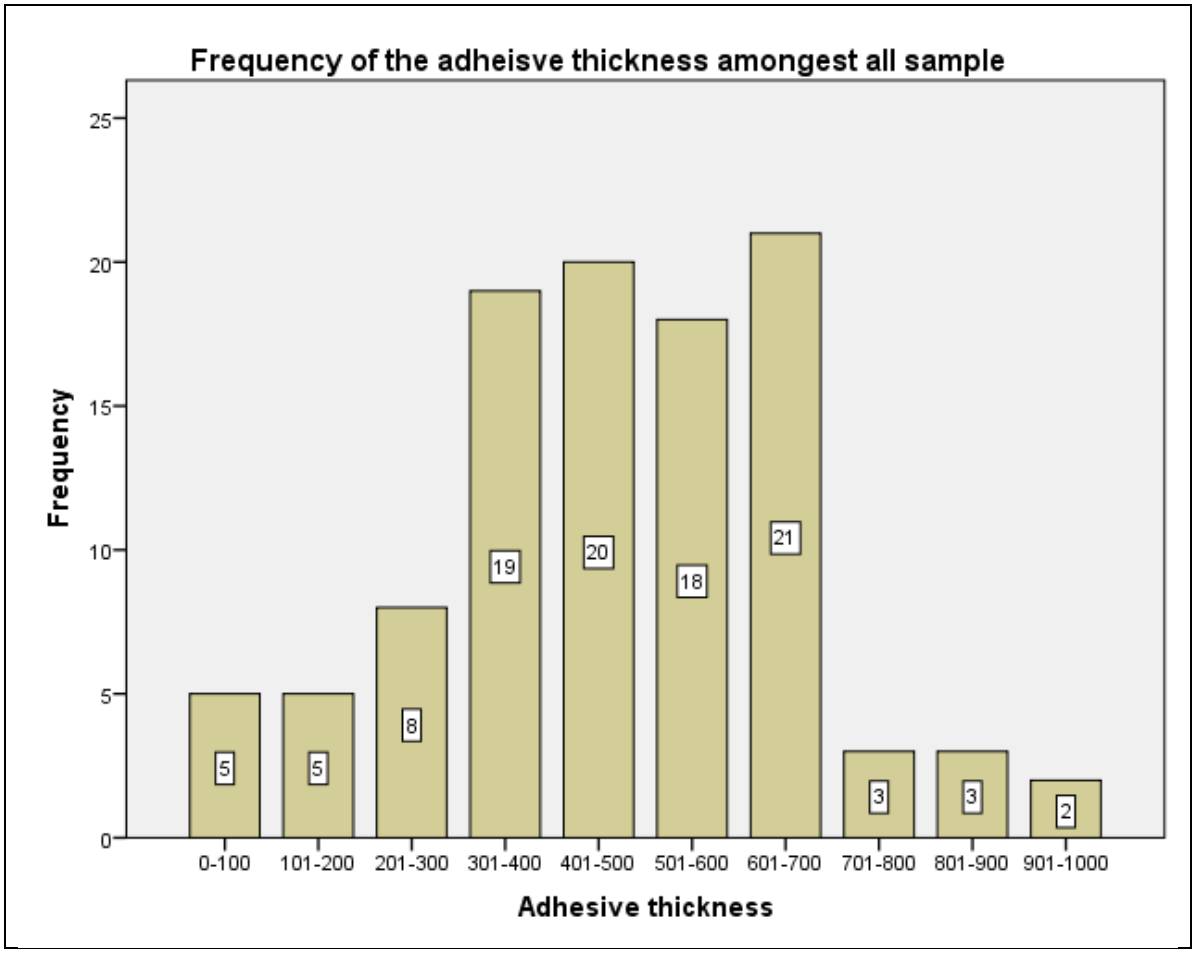


Figure 5.4: frequency of the adhesive thickness applied by the same operator

As can be seen from Figure 5.4 the adhesive thickness measurement showed that 77 out of 104 (74%) of the sample revealed a thickness ranging between 301 and 700 µm. However only 8 out of 104 (7.7%) presented a thickness ranging between 701 and 1000 µm. This is substantially low in comparison to the number of samples which had thickness of between 301 and 700 µm. Only 10 samples showed a thickness between 0 and 200 µm.

5.9 Discussion

5.9.1 Adhesive pooling

The manufacturer states that the mean film thickness for Optibond Solo plus adhesive is 10 µm (Kerr, 2009). That may have been measured on a flat experimental surface. From the results of this study the variabilty of the adheisve thickness ranged between 36.55 to 930.92 µm with a mean thickness of 465.9± 192.47µm. This variabilty in thickness was reported by Grossman and Setzer (2001) for a class I restoration comparing the thickness achieved by using two adhesive systems (filled and unfilled adhesive) in which the measured thickness for the Optibond Solo plus was ranged between 0 to 1150 µm with a mean thickness of 221± 130 µm. They found that the cavity site played a role in the adhesive thickness and resulted in inconsistency of bonding agent thickness along the cavity wall. Optibond Solo plus (adhesive material) showed a maximum thickness at the cavity angle which then decreased toward the cavity margin. They attributed the significant difference found between the two systems to the type of bonding agent (filled or unfilled adhesive). This finding was in agreement with the current study as the adhesive revealed a maximum thickness at the axio-cervical angle and decresased toward the margins.

In the current study, adhesive pooling at the cervico-axial angle of the resoration led the thickness to be greater than the manufacturer's claimed optimum thickness. The uniformity of the adhesive material throughout the interface could have a great impact on the elastic buffering role of the bonding agent which relies on the even distribution of the physical and mechanical

forces generated by polymerisation shrinkage, temperature changes and masticatory forces (Opdam et al., 1997; Staninec et al., 1995). As stated by Peter et al (1997), adhesive pooling at the cavity angle arises as a result of increased viscosity of the filled adhesive and the technique of air thining is unable to evenly distribute the high viscous adhesive material throughout the cavity wall because of the “damming” effect of the preparation angle.

Differences in the adhesive thickness was cited to be related to different variables including air thining; application technique; viscosity and incomplete curing of the bonding agent (Griffiths and Watson, 1995; Opdam et al., 1997; Staninec et al., 1995). Any of the above mentioned variable could by applied to this study.

A literature review revealed some controversy in relation to a finding on adhesive thickness. Opdam et al. (1997) suggested that a thick adhesive layer could prevent gap formation between tooth and restoration and perform as an elastic buffer when compared with thin layer. However, Hilton and Schwartz (1995) found that a thick adhesive layer adversely effected the longevity of the restoration by increasing crack propagation and minimizing bond strength. Also de Menezes et al, (2013) stated that excess adhesive may negatively affect bond strength of the adhesive material to the tooth structure.

Film thickness of the adhesive material has to be of an even thickness along the entire restored cavity with the purpose of ensuring consistent bonding and uniform stress distribution (Grossman and Setzer, 2001).

5.9.2 Absorption of the silver nitrate by the adhesive

Following the finding that the resin took up the silver nitrate, the literature was again reviewed to investigate why this may have occurred.

The hydrophilic nature of the adhesive used in the study was speculated to be the reason why the material was permeable to the silver nitrate dye as stated by Yiu et al.(Yiu et al., 2005). The sample of this study were kept wet at all times to avoid dryness which may consequently result in further water sorption leading to a propagation of water trees in resin matrices which could be permeable to small ions such as silver nitrate.

Hydrophilic monomer was added to the adhesive material by the manufacturer for the purpose of promoting effective bonding between hydrated dentine and resin composite. It was however, reported to cause extensive amount of water sorption

which not only affects the mechnical stability but also compromises the durabilty of resin–dentine bonds (Malacarne et al., 2006; Yiu et al., 2004).

In this study, as all the samples showed that the adhesive material had taken up the silver nitrate dye, the dye penetration test was considered to be invalid test

to assess the microleakge in this situation. Going back to Chapter 4, it was assumed that the vast majority of the samples leaked to the highest score of 4. This assumption is now believed to be incorrect and on reviewing the photograph Figure 4.14 it clearly shows that the pattern in which the dye penetrated the dentine may come from the adhesive side which absorbs the silver nitrate and acts as a reservoir which leads to the spread of the dye into the dentine.

A recent study by Malacarne-Zanon et al (2010) claimed that hydrophilic dental adhesive material performs as permeable membranes after polymerization, which allow water to flow through the adhesive layer. The greater permeation and deposition of silver tracer within the adhesive material was interpreted as a visual show of the water diffusion process and greatly attributed to the material's hydrophilicity which facilitate water sorption of these adhesive system. This finding has been confirmed by Yiu et al (2006).

5.9.3 Application of the resin modified glass ionomer cement

The clinical procedure which was employed in the sandwich restoration with resin-modified-glass ionomer cement as a base was by applying the cement on the base of the preparation, polymerizing it and then etching the cement. The final restoration was then built up using resin composite (Liebenberg, 2005).

The aim of this study was to examine the effect of co-curing the resin modified glass ionomer with resin composite, in relation to the microleakage of the sandwich restoration. Accordingly, etching the RMGIC was not possible.

The result of this study has shown that the failure was mostly within the adhesive layer which revealed crack propagation. In actual fact, good adhesion, in certain cases, may result in an undesirable outcome of crack propagation into the dentine due to stresses within the material (Czarnecka et al., 2014).

5.10 Conclusion

The Dye penetration test failed to show a difference between the two techniques (separate curing and co-curing) due to dye absorption by the adhesive resin. The stereomicroscope examination showed no difference between the two techniques. However, the adhesive thickness varied considerably between the samples.

Adhesive pooling was still evident without the use of the matrix band.

The thickness of the adhesive layer was far thicker than manufacturer's recommendations which was 10 microns.

5.11 Summary:

To summarise the findings from this part of the study, the adhesive material was found to pool in the cervico-axial angle of the restoration. Crack propagation associated with the pooled adhesive could potentially cause early restoration failure. It was not possible to assess the degree of dye penetration, due to the uptake of silver nitrate by the adhesive resin. The majority of samples showed an unacceptably thick resin layer Based on these findings, it was important to investigate the effect of the adhesive thickness on the stresses generated.

Therefore, FEA was conducted aiming to evaluate the effect of the adhesive thickness on stress generation.

The film thickness of the adhesive was greater than the manufacturer's recommendation of 10 micron, which could mean that even when the application instructions were followed, the required thickness could not be achieved. This therefore implies that the manufacturer's instructions may have not been sufficiently detailed or specific to ensure that the appropriate thickness would be achieved in all cases when an operator complied with the instructions fully. It might also mean that even if detailed instructions were developed there might be factors that could influence the thickness which were not easy to control.

In this case, a single investigator conducted the experimental restoration placement, however, varying results were produced. In view of this a number of further investigations were planned in order to identify why such variation in thickness of the adhesive layer had occurred. These investigations included:

1.Angulation of the tooth during application and curing.

2.Inter-operator factors and compliance with the manufacturer's instructions.

The next chapter presents the FEA to investigate the effect of the adhesive layer thickness on the stresses generated.

Chapter 6

A.Tooth angulation and its effect on the adhesive thickness

6.1 Introduction

As can be seen from the current research presented in chapter 5, much variability in the thickness of the adhesive layer was noted. Adhesive pooling in the cervico-axial angle of the restorations was predominant in most of the samples. All of the experimental work was accomplished on the flat laboratory bench in which the prepared cavity was positioned facing upward at right angles to the bench. It was hypothesised that one possible factor that could affect the adhesive thickness and consequently affect the bond strength could be the position of the tooth in both maxillary and mandibular arch and its angulation.

The position of the tooth either in maxillary or mandibular arch has been thought to have an effect on the longevity of the restoration (Demarco et al., 2012). To date, no previous research was found showing the effect of tooth angulation and its position on the thickness of the adhesive layer.

6.2 Aim:

The aim of this experiment was to investigate the effect of tooth angulation during placement of the adhesive resin on the adhesive thickness.

6.3 Materials and methods:

In an attempt to control the variables associated with variability of the tooth structure and acid etching techniques, typodont teeth (Frasaco Gmbh, Germany) were used in this experiment. The acid etching stage was omitted in this experiment to focus more on the adhesive application technique.

A small bench top device was constructed (Figure 6.1) in order to simulate different angulations of the teeth in patients' mouths during tooth restoration.

The device was composed of three pieces of rectangular wood. One of the pieces was positioned as a backboard, the other piece was a horizontal stationary board that was fixed to the backboard and the final piece was attached to the horizontal board with a hinge. The hinged element could be held against the backboard at 12 different angulations relative to the horizontal (15º, 30º, 45º, 60º, 75º, 90º, 105º, 120º, 135º, 150º, 165º, 180º). At each angle a hole was drilled so that a nail could be slotted in; to allow the hinged element to rest at the required angulation.

An upper typodont jaw with a prepared upper second left premolar tooth (Frasaco Gmbh, Germany) was secured to the hinged element of the device (Figure 6.1). The number of teeth used for this experiment was 24 typodont second left premolar teeth, two teeth per angle starting at 0º angle to 180º angle.

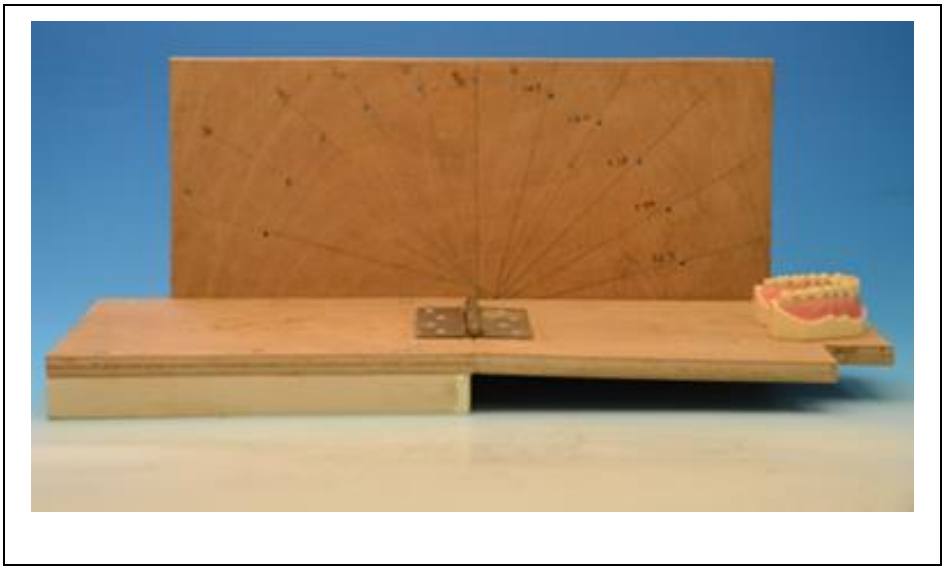


Figure 6.1: Device for simulating tooth angulation in the patient mouth

Class II mesial slot cavities were prepared in the typodont upper left premolar teeth.

The dimension of the slot were as follows (Figure 6.2):

Bucco-palatal width 3 mm.

Cervical wall width 2 mm.

Cervico-occlusal height 6 mm.

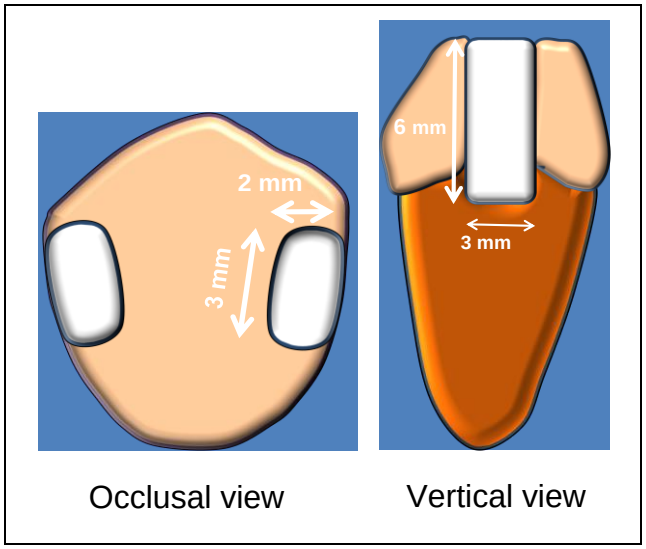


Figure 6.2: Dimensions of the slot cavities

All the preparations were standardised using fine-pointed water proof pen (Lumocolor, Staedtler, permanent black marker) to mark the occlusal outline of the preparation which was determined using a periodontal probe (Michigan O probe with Williams markings which has circumferential lines at 1, 2, 3, 5, 7, 8 , 9, and 10 mm) as in Figure 6.3.

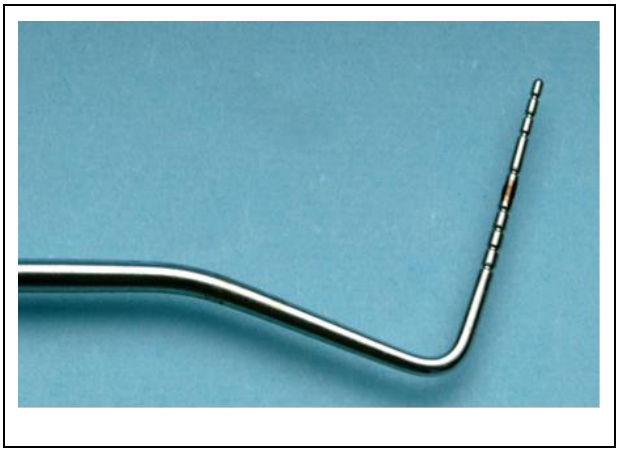


Figure 6.3 : Periodontal probe used to measure the extent of the preparation

All of the slot cavities were prepared in each tooth using a water-cooled diamond bur held in a high speed handpiece (KAVO Dental Excellence, Biberach, Germany).

To ensure consistency of the preparation size, a check was performed on each preparation using a periodontal probe to determine if any inaccuracy in the dimensions of the preparation had occurred. Any faulty preparations were discarded and replaced.

Optibond solo plus adhesive (Kerr,USA) was applied to the cavity surface with a disposable sponge tipped applicator, according to the manufacturer instructions (Table 6.1) at different angulation see Appendix E.1.

Table 6.1: Manufacturer instructions for Optibond solo plus

Material	Manufacturer instruction
OptiBond Solo Plus (unidose) Kerr corporation	1. Apply to enamel/dentine surface with applicator tip for 15 seconds, using light brushing motion. 2. Air dry for 3 seconds. 3. Light cure for 20 seconds.

6.4 Tooth sectioning

Each tooth was secured on a round plastic disc using warmed green stick compound (Kerr, USA). The plastic disc was then tightly screwed on the sectioning machine (precision diamond wire saw with constant water coolant) (Figure 6.4).

Each Typodont tooth was sectioned twice in the midline mesio-distally using a diamond wire saw with constant water coolant, to give a tooth slice of about 1mm thick to be examined under the stereomicroscope for adhesive thickness measurement. Motic camera (digital microscope camera), connected to a laptop, was inserted in the microscope tube to measure the adhesive thickness. Calibration of the camera software for accurate measurement at x20 magnification was undertaken prior to measurement. The adhesive was measured at the greatest area of thickness. All measurements were performed by the main investigator.

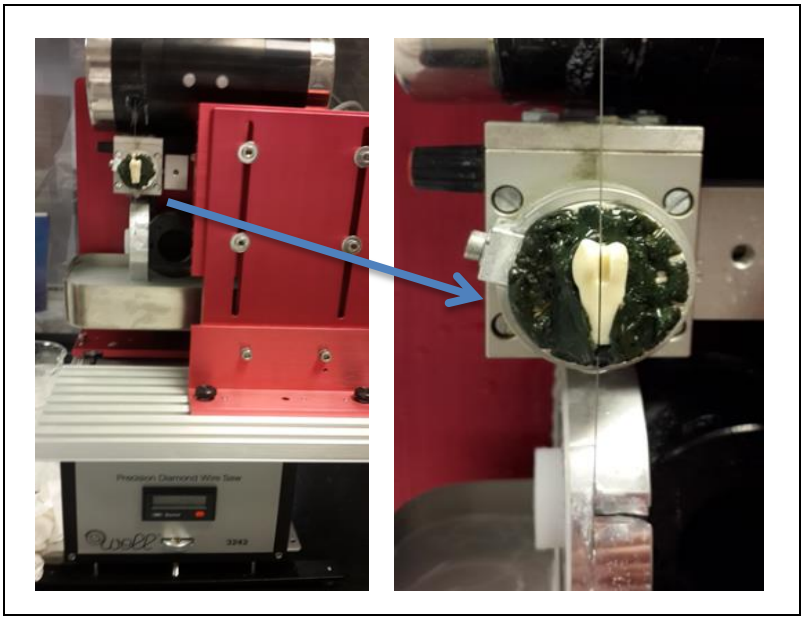


Figure 6.4: Tooth sectioning using precision diamond wire saw

6.5 Result:

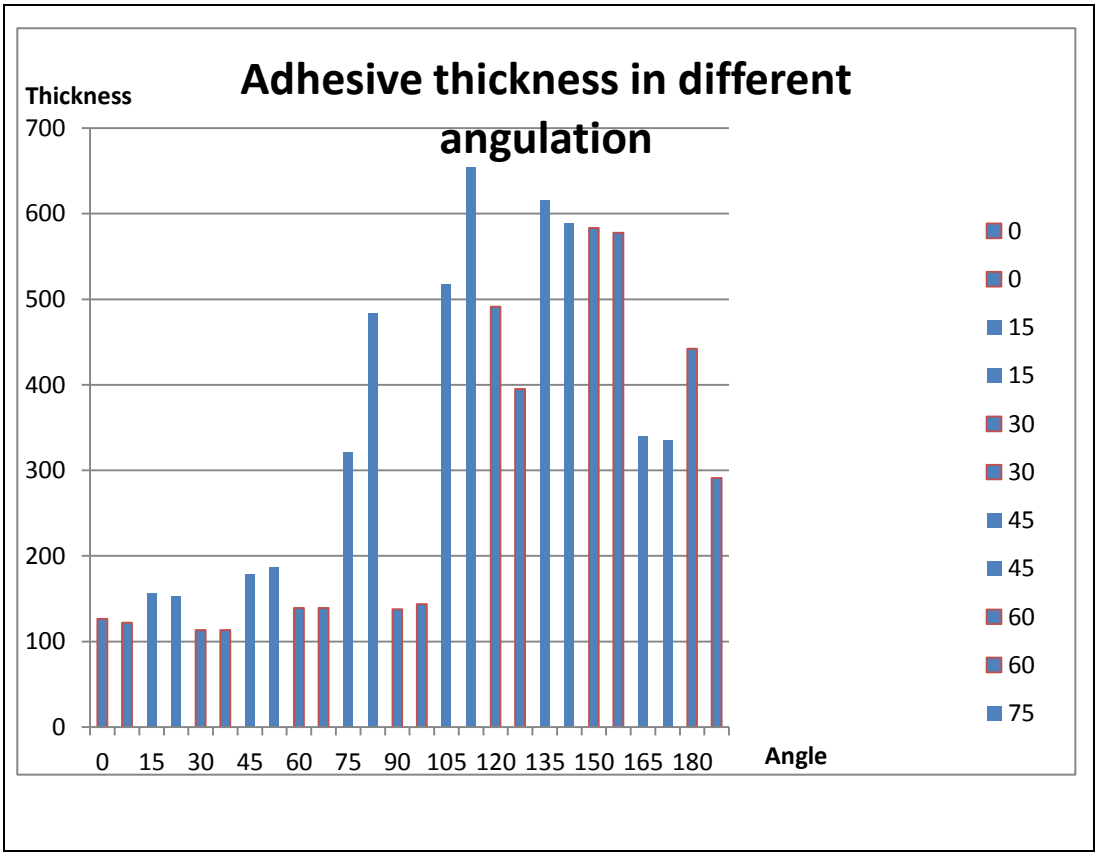


Figure 6.5 : Adhesive thickness at different angulations

Figure 6.5 shows the adhesive thickness at different placement angulations, carried out by the main investigator (Appendix E.3). From the graph, it can be seen that there was no clear trend in relation to the effect of placement angulation on the thickness of the adhesive layer. However, it can be seen that with one anomaly, a lower value for thickness of the resin layer was recorded until the jaw was placed at 105°. The anomaly occurred at tooth 11 at an angle of 75° with the adhesive thickness of 320.8 µm and at tooth 12 at the same angle with a thickness of 483.2 µm. All measurements of adhesive thickness at angulation of 105° and greater, showed considerably greater values than at 90° angulation and below with the exception described at 75°. There was also variability in the thickness between the two teeth investigated at the same angle.

As a final point, the thickness of the adhesive varied considerably, even between the teeth treated at the same angle. There appeared to be a trend towards greater adhesive thickness when applied to the jaw at angles greater than 90°.

6.6 Discussion

As can be seen from this experimental work although there was no clear trend in terms of increasing the adhesive thickness with the rise in the angulation, it was clear that angulation of the tooth may play an important role in allowing pooling of the adhesive in the corner of the cavity which may be due to gravity. This result was in agreement with the finding by Lee et al (2007) who found that a thicker adhesive area can be measured in the internal line angle of the cavity

while a thinner area can be measured in the cavity margin and the half way cavity wall showing the effect of gravity causing pooling of adhesive at the internal line angle of the preparation, when the current experiment replicates the position of a tooth in lower arch (angulation of 105° and above), with the cavity facing upward. Adhesive pooling was also found especially at the line angle of the preparation. When the tooth is in the maxillary arch (angulation 90° or less) with the cavity facing downward this could allow the flow of the adhesive outside the cavity and reduce the chances of adhesive pooling.

The uniform film thickness (10 µm) that was suggested by manufacturer in order to achieve durable and successful adhesive may therefore be difficult to obtain clinically in all sites around the mouth.

The uniform thickness of the adhesive which is claimed in the literature was mostly produced on the flat surface of a tooth. However, adhesive applied in a proximal slot cavity (as the case in this study) could result in a thicker adhesive as the shape of the cavity and the gravity effects can cause the adhesive to flow into the line angle of the preparation (adhesive pooling) which may lead to a higher contraction stress at this site (Choi et al., 2000).

9.7 Conclusion:

Angulation of the tooth during adhesive application may have an effect on, adhesive pooling and lead to a thick adhesive layer.

B. Investigating the effect of application technique on the adhesive thickness:

From the previous experiment A, the main finding was that the thickness of the adhesive layer was not consistent, even in teeth treated at the same angle. A further experiment was conducted in order to check the technique sensitivity when the adhesive application was completed by different operators.

6.8 Aim

The aim of this experiment was to determine operator compliance with the manufacturer's application instructions and to investigate the effect of any deviation from these instructions or inconsistencies in technique on the thickness of the adhesive layer.

6.9 Materials and methods:

Ten clinical dental restorative postgraduate students were recruited to the study to apply the adhesive. The same method of placement was followed as in the previous experiment. Written manufacturer's instructions for use were given to each postgraduate student to be followed during the application.

The techniques of adhesive application by the postgraduate students were monitored by the main investigator who recorded the techniques in details.

The main investigator (subject 11) (Figure 6.6) also took part in this experiment.

6.10 Result

Figure 6.6: Manufacturer instruction and different interpretation by the operators (from operator 1-11)

Figure 6.6 shows the manufacturer's instructions for Optibond solo plus adhesive material and the adherence to and variation within the use of the instructions. As can be seen from the Figure the manufacturer instructions only included three main steps with a brief explanation for each step. The green colour code refers to the instructions stated in the manufacturer instruction for use, any one followed the same steps was coded with the green colour, while the orange coded colour was the detailed criteria for each step as interpreted by different operators, however, the white code denoted an operator who did not carry out that step of application at specified angles.

The first step of the instruction which stated "apply the adhesive to the enamel and dentine surface" did not give the operator a clearly defined method of application. Therefore, as a consequence of this ambiguity, various methods of application arose. One operator may submerge the brush into the pot and pull it out without scrapping the margin of the container, as the case with operators (2,3,4,5,6,7,8,9,10,11); whilst another operator, may only insert the tip of the brush and wipe the margin of the container as can be seen with operator number 1 at 75º. There are many different methods that could have been used in putting the adhesive on the brush.

This part of the instruction was however, only the first step; the second part was applying the air for 3 seconds. Again various different techniques could have been used in the application of the air which include; positioning of the tip of the air syringe either close to or far away from the tooth margin; strength of the

applied air (light, medium, strong); nature of the applied air (continuous, interrupted), Length of air application (3 seconds or more).

The initial position of the air syringe poses a very large problem, as some may position it very close to the occlusal margin as can be seen with operator (1,3,4,5,7,8,9,10,11) of the tooth whilst others might perhaps use a different angle and distance when attempting to position the syringe for air thinning as in operator (2). It was also noted that same operator may employ different positioning of the air syringe close to the tooth margin in one situation and far away from the tooth margin in the other 3 situation as the case in the operator number (6).

Another aspect of the instruction which was left to the chance was the strength of the applied air thinning. Whilst one operator used a very strong air as in operator (2), another may only apply the air very gently as the case of operators (1,4,7,8,10,11), medium force air blow was also applied as in operator (6). The difference in the application technique in relation to this criterion could be clearly seen with the same operator who showed inconsistency in the application technique as operator (3.5.9). This factor is quite significant in determining the outcome of the experiment.

The ambiguity of the instruction in relation to the air application was factor that could influence the final result of the experiment. As there were two potential

ways of approaching this aspect, either by application of a continuous (operator 1,3,4,5,6,7,10,11) or interrupted air stream (2,8) which also shows inconsistency of the same operator as in operator number (8,9).

The length of air application has shown a difference between operators while some applied it for the specified time by the manufacturer for 3 seconds as in operator (5,11), others were either applied for less than 3 seconds as in operator (4,10) or more than 3 seconds as in operator (1,2,6,8,9), inconsistency even with the same operator was also shown with operator (3,7).

The only steps followed by all operators as specified in the manufacturer instructions were the adhesive application time which was “alarm” timed at 15 seconds, and the light curing time of 20 seconds which was timed by the curing light machine.

Table 6.2.: adhesive thickness measured at 75 and 90 degree angle (different operators)

Tooth	Angle	Thickness	operator
1	75	182.7	1a
2	75	121.9	1b
3	90	40.6	1c
4	90	170.6	1d
5	75	227.4	2a
6	75	154.3	2b
7	90	143.7	2c
8	90	143.9	2d
9	75	219.3	3a
10	75	211.2	3b
11	90	300.5	3c
12	90	775	3d
13	75	361.4	4a
14	75	173	4b
15	90	337.1	4c
16	90	207.1	4d

17	75	109.5	5a
18	75	269.9	5b
19	90	193.5	5c
20	90	121.9	5d
21	75	189.7	6a
22	75	134	6b
23	90	391.8	6c
24	90	405.4	6d
25	75	328.9	7a
26	75	269.4	7b
27	90	100	7c
28	90	288.3	7d
29	75	194.1	8a
30	75	174.6	8b
31	90	77.6	8c
32	90	345.2	8d
33	75	219.3	9a
34	75	159.1	9b
35	90	190.9	9c
36	90	160.4	9d
37	75	179.8	10a
38	75	192.6	10b
39	90	194.9	10c
40	90	182.3	10d
41	75	320.8	11a
42	75	483.2	11b
43	90	137.5	11c
44	90	143.5	11d

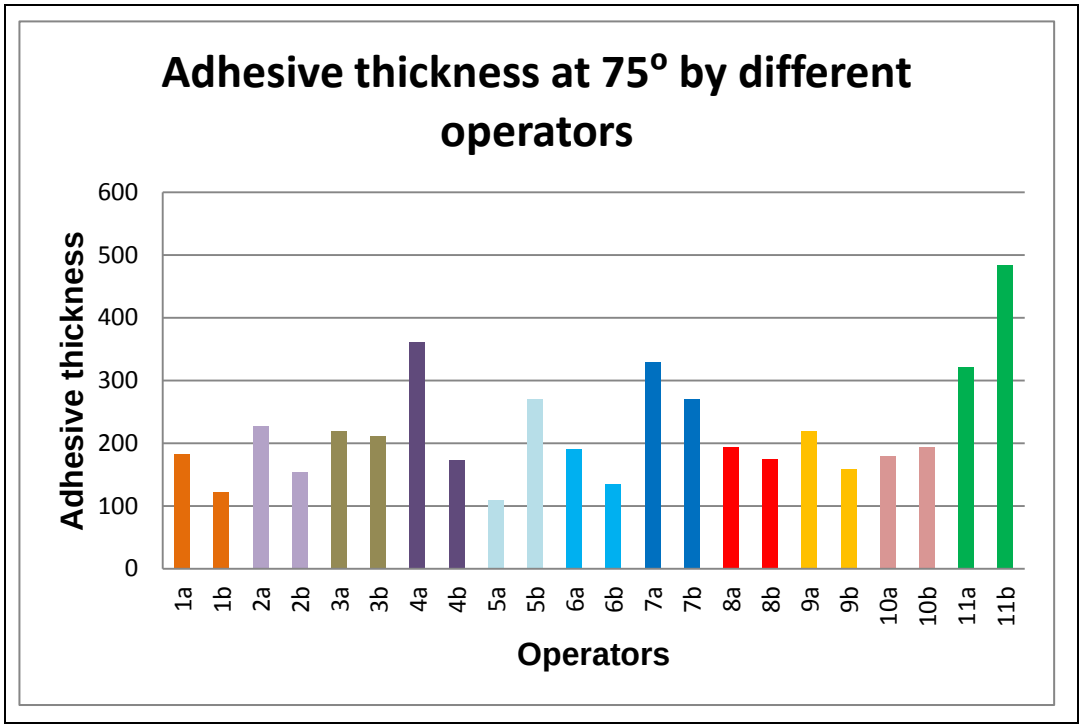


Figure 6.7: Adhesive thickness at 75° angle by different operator including main investigator (11)

Figure 6.7 represents the data collected from measuring the adhesive thickness, at the 75º angulation. All operators achieved varied results from the same experiment. Consequently, different operators interpreted these limited instructions in different ways (Figure 6.6). Some operators managed to acquire same results; they have however used different application techniques.it can be seen from Table 6.2 in teeth numbers 3a and 9a, operator produced an adhesive thickness of 219.3 µm. In tooth 3a operator applied the adhesive with strong up and down brushing motion and immersed the brush for a second time in the adhesive container and continued the application for the 15 seconds, the air syringe was close to the tooth margin and the strength of the air was a strong continuous blow. Tooth 9a operator had however, used light up and down brushing motion and immersed the brush only once, the air syringe was close to the tooth margin with a very light air blow and used three interrupted air blow for more than 3 seconds.

Most other results did not have any other similar sets of data, as they all used less consistent ways of applying the adhesive. For example, the difference in adhesive thickness between tooth 1b and tooth 11b is markedly different with 361.3 µm between the two readings. The significant difference in application between these two samples is the time for which the air had been applied and also the immersion of the brush for a second time during adhesive application to the tooth 11b. It was also clear that same operator showed very different results even at the same angulation which meant that they have altered the way they applied the adhesive between each tooth. An example of this would be tooth 4a in which the adhesive thickness was fairly high at 361.4 µm and then it drastically decreased to 173 µm in 4b, although they have followed the same method they have achieved very different results. The differences can also be seen in teeth 6a and 6b teeth where the measured adhesive thicknesses were 189.7, 134 µm respectively, the only difference in the application was that the air syringe was close to the margin of the tooth 6a and far away from the margin in tooth 6b.

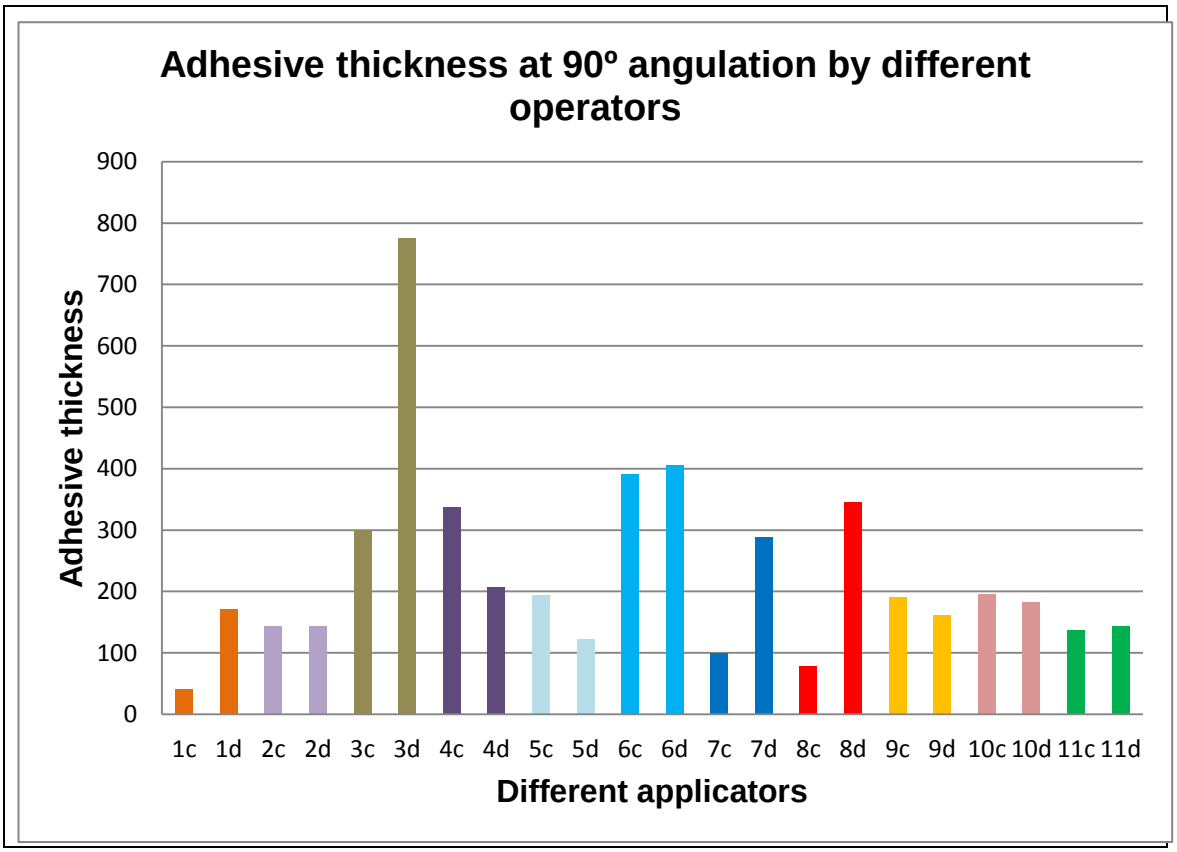


Figure 6.8: Adhesive thickness at 90º angulation by different operators

Figure 6.8 shows data collected from measuring adhesive thickness at 90º angulation. In this graph the majority of operators also recorded different data. Although the same device and angle had been used, only one operator was able to achieve almost identical results and this was in teeth 2c and 2d. The adhesive thickness was 143.7 in 2c and 143.9 µm in 2d. This operator followed the exact same method each time which meant that he was able to achieve the same result.

Other operators kept to the same technique at each time, yet have acquired very marked differences in the results, as with operators 1,2,4,6,7,10,11 at c and d tooth number. For example, operator 1 achieved 40.6 and 170.6µm adhesive thickness at teeth 1c and 1d respectively and operator 11 who

acquired an adhesive thickness of 483.2 and 173.5 µm at teeth 11c and 11d respectively.

Another operator who followed different techniques and also achieved different results was the operator 3 at teeth 3c and 3d. The adhesive thickness in 3c was 300 µm whilst 3d was 775 µm this was a difference of 475 which is significant considering that the same operator was applying the adhesive material. Observation showed that the air strength was drastically different. On tooth3c it was strong and continuous whilst on 3d it was light and continuous. Moreover, the time of air application was also different. The operator air dried the adhesive layer in 3c for more than 3 seconds whilst in 3d it was dried for less than 3 seconds. Both of these factors contributed to the significant variation between the two teeth.

6.11 Discussion:

A systematic review by (Demarco et al., 2012) of publications between 1996 and 2011 concerning adhesive posterior composite restorations concluded that the patient, operator and material could play an important role in the success and the longevity of the restoration. From the current experiment in which different operators followed the same manufacturer's instructions supplied with the adhesive material used in the study, it was clear that every operator was interpreting those instructions in different ways. As recommended by Finger and Balkenhol (1999) the manufacturer should provide a more clear, detailed and unambiguous description for the application technique in their instructions so that the operator could follow them pedantically to achieve a satisfactory result

and also avoid operator variability. In order to obtain a consistent, predictable and reliable clinical result, Hiraishi et al (2007) suggested that the manufacturer's instructions should meticulously describe how to dry adhesive.

Technique sensitivity of dental adhesive is a well-documented subject in the literature. Previous research has demonstrated that bond strength is significantly influenced by the technique variability of the operators (Miyazaki et al., 2000). Particularly the total etch adhesive, which was more sensitive to operator skill than the self-adhesive system (Giachetti et al., 2007) and revealed its efficacy only when applied by skilled operator. The total etch adhesive system used in this study was condemned for its technique sensitivity which may compromise bonding efficacy and marginal seal of this type of adhesive as stated by (Frankenberger et al., 2000; Peschke et al., 2000).

Since the introduction of the total etch adhesive system and wet bond technique (Kanca, 1992), the manufacturer's instructions for use appears to follow the same protocol with very brief instructions for use (Barkmeier et al., 2009; Soappman et al., 2007; Lopes et al., 2006; Vargas et al., 1997). This includes instructions to etch and condition the prepared tooth surface to remove the smear layer, wash, dry and apply the adhesive with light brushing motion, air thinning, then curing. Each step was applied for a period of time suggested by the manufacturer instructions for use. All of the previous steps when a detailed description is not included could demonstrate variation even between qualified and experienced clinicians or potentially the same clinician undertaking the

procedures at different times. From the main investigator point of view, each step should be explicitly defined to ensure the accuracy and consistency of the adhesive application.

All operators achieved varied results from the same experiment. This could be due to the imprecise nature of the manufacturer's instructions for the adhesive placement

Even though the instructions may have been imprecise, some operators managed to acquire similar results.

6.12 Conclusion:

From the results of this study, it can be concluded that:

Adhesive application is a sensitive multi-stage procedure and further work may be needed to develop a consistently thin adhesive layer.

Lack of detailed and vague instructions could lead to many different interpretations which could affect the accuracy and consistency of the experiment. More attention should be given by the manufacturer to explain each step of the instruction explicitly in order to avoid any problem which could consequently lead to restoration failure

Multiple variables such as air thinning, position of the syringe and also time of air application could result in considerable differences in the adhesive thickness.

Chapter 7

Development of numerical tooth model

The second stage in this study was to develop a tooth model to accomplish the finite element analysis by first gathering the material properties for both the restorations and the tooth structure and second by development of numerical tooth model.

7.1 Gathering mechanical properties for the restorative material and the tooth structure.

The literature was reviewed and the mechanical properties for both the restorations and the tooth structure were collected. This information was then put together as Table 7.1.

Table 7.1: Properties for the tooth and restorative material

Material	Elastic Modulus E (GPa)	Poisson's Ratio ν	Compressive Strength σ_C (MPa)	Tensile Strength σ_T (MPa)	Shear Strength τ (MPa)	Thermal Expansion α ($/^oC$ x10^{-6})	Volumetric shrinkage (ΔV/V) %
Adhesive material (Optibond Solo) [1, 18]	1	0.3		25			9.04 [Determined in chapter 9]
Bonded with Enamel					34[15]		
Bonded with Dentine					31.3 ±2.7[18]		
Dental plaster (Calestone)[7]	11.7	0.19	56.5[32]	4.83 – 5.52	14.5[32]		
Dentine [1, 2, 3, 4, 9, 16]	18	0.31	297[8]	105[8]	138[27]	11[20]	
Enamel [12, 16, 25,26]	80	0.3	384[8]	10[8]	90[27]	17[20]	
Pulp [9, 16, 26]	$2.07x10^{-3}$	0.45					
Resin composite Herculite XRV [1,9, 10]	9.5	0.24	380[30]	52[30]	15.4±3.7[14]	32.6±1.6[30]	2.73±0.31[1]
bond Optibond					17.61±4.34[13]		
Glass Ionomer Cement, Fuji II LC [6]	20	0.3[11]	200	15	62.6[22](a)	10.2 - 11.4	2.53[21]
					70.2[22](b)	Average used. 10.8	
					68.9[22](c)		
bond with dentine				21.8 [29]			
Z100[5,17, 21, 33]	15.200[17]	0.28[17]	161.22[5]		29.3±7.2[21]	22.5±1.4[30]	2.80[33]

(a) 1 day after light activation, (b) 3 days after light activation, (c) 9 days after light activation

The references included in the table were numbered to fit the table and are listed below in the same style (Harvard) used throughout this thesis.

[1] Ausiello et al. (2002), [2] Ausiello et al. (2001), [3] Ausiello et al.(2004), [4] Barink et al. (2003), [5] Brandao et al. (2005), [6] (COOK, 2000), [7] L Cridland and Wood (1968), [8] Dhuru (2004), [9] Dejak and Mlotkowski (2008), [10]

Ensaff et al.(2001), [11] Frankel et al. (1998), [12] Ichim et al. (2007), [13] Jumlongras and White (1997), [14] Kamel et al. (1990), [15] KERR. [16] Kowalczyk (2009), [17] Kwon et al. (2009), [18] LU et al. (2008), [20] Magne et al. (1999), [21] Mondragon and Soderholm (2001). [22] Mount et al. (2002). [25] Rees and Jacobsen (2000), [26] Rodrigues et al. (2012), [27] Sakaguchi and Powers (2012), [29] Tanumiharja et al. (2000). [30] Taylor et al. (2008), [32] Williams (1979), [33] Yazici et al. (2004).

7.2 Model development

The preliminary model of the maxillary second premolar was generated primarily by using CorelDraw software (CorelDraw x6). The tooth dimensions were sought from Wheeler's dental anatomy book (Nelson et al., 2010). The enamel thickness was averaged to 1.54 mm and dentine at about 3.27 mm (Shillingburg and Grace, 1973). Half of the tooth was modelled using axisymmetric line, the tooth morphology was de-featurized in order to simplify the model and obtain a preliminary result.

The restored part of the tooth was captured from the tooth section of the restored tooth from the previous experimental work presented in Chapter 4. The tooth section was placed on a photographic paper with scales on both the upper part and the left side of the paper which was then photographed (Figure 7.1).

The tooth photograph was imported into CorelDraw software, the angulation of the tooth was then corrected by drawing a line in the middle of the tooth (central

line, CL) and the photograph was then adjusted to position the tooth section at right angles using the central line as a reference (Figure 7.1).

The restoration area was then sketched, the curved area was represented with circles and the straight areas with lines and the distance to each component was measured using CorelDraw software (Figures 7.2, 7.3).

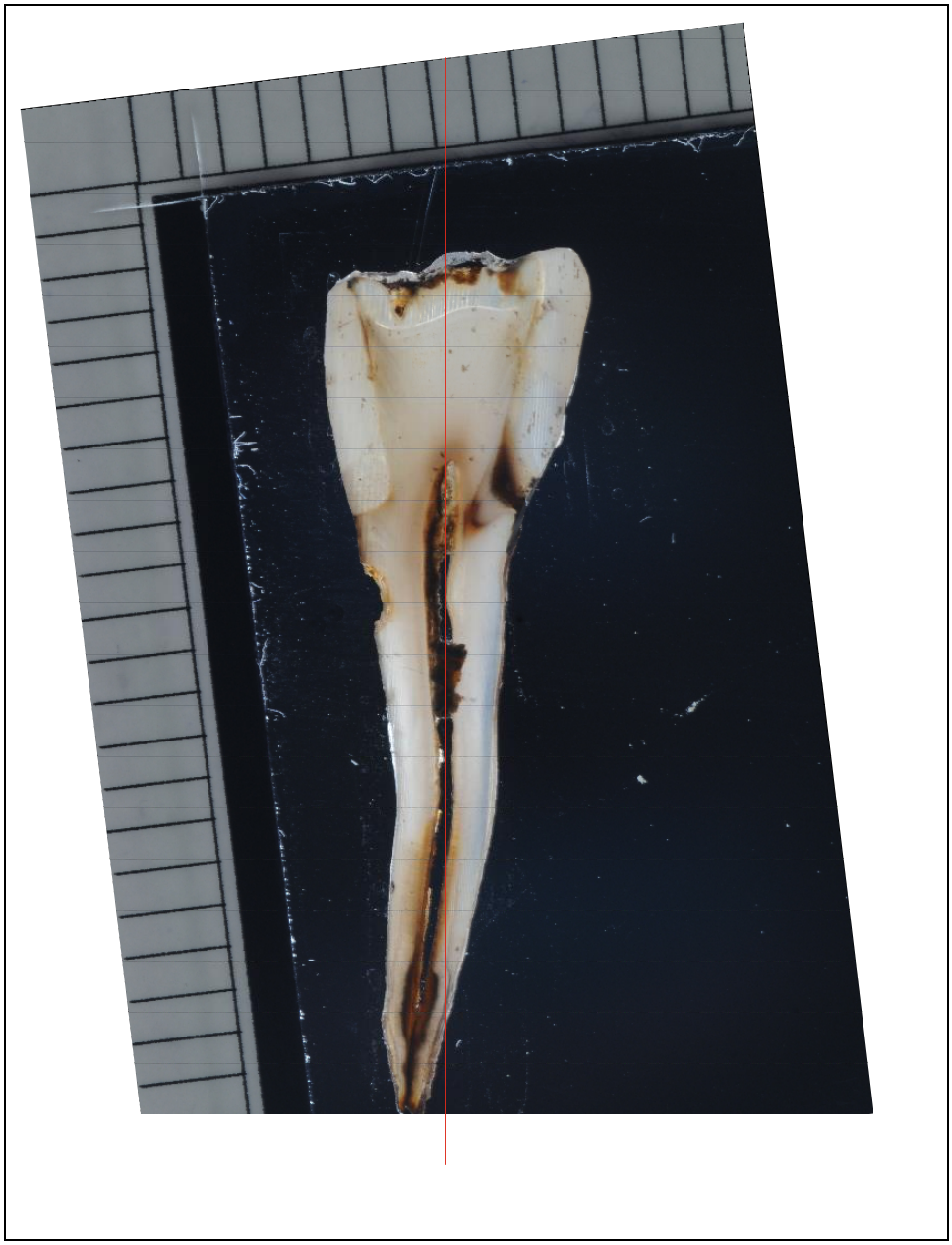


Figure7.1: Adjustment of the tooth angulation

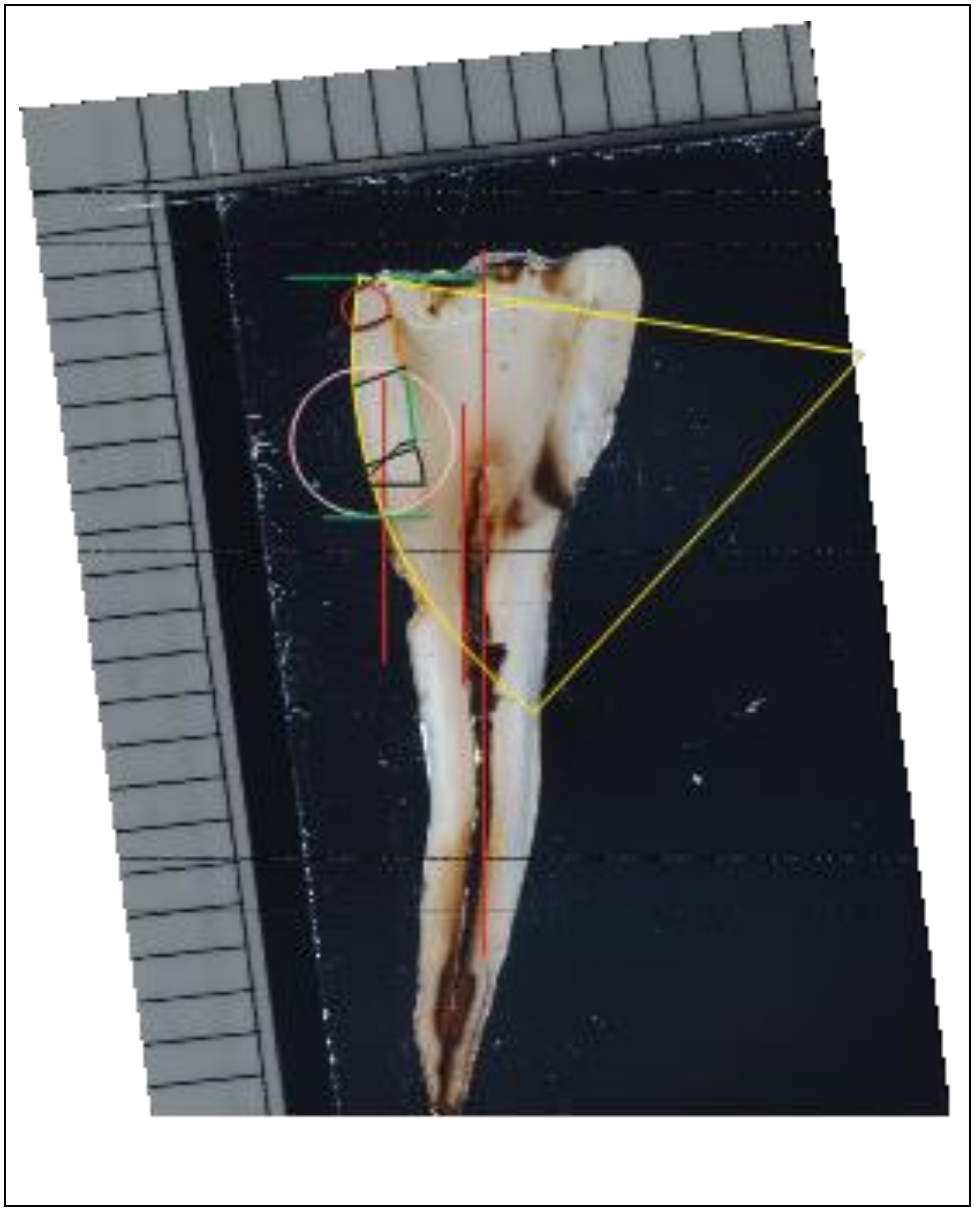


Figure 7.2: Capturing the restorations outline

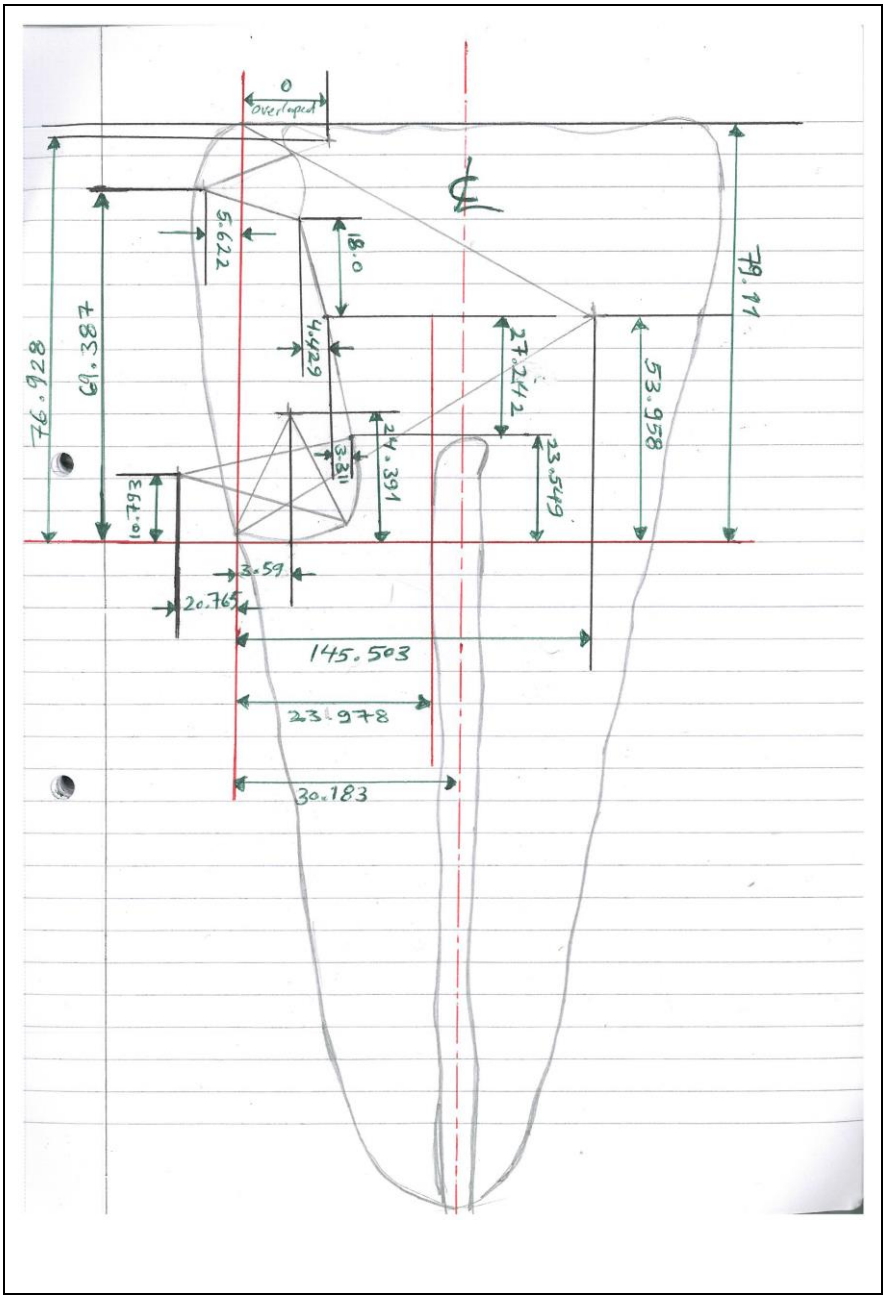


Figure 7.3:First sketch of the tooth with the restoration from measurments extracted using CorelDraw

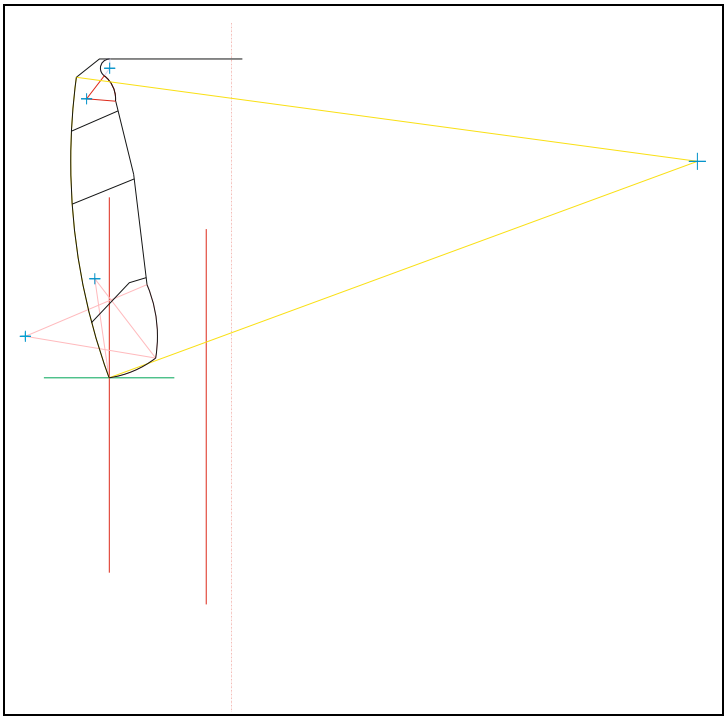


Figure 7.4: Outline of the tooth restoration

The sketched outline of the restoration (Figure 7.4) was inverted about the vertical axis to the right direction to match the restoration part of the preliminary model (Figure 7.5) and superimposed on the preliminary model. The sketched outline of the restoration was then scaled to match the dimensions of the preliminary model (Figure 7.6).

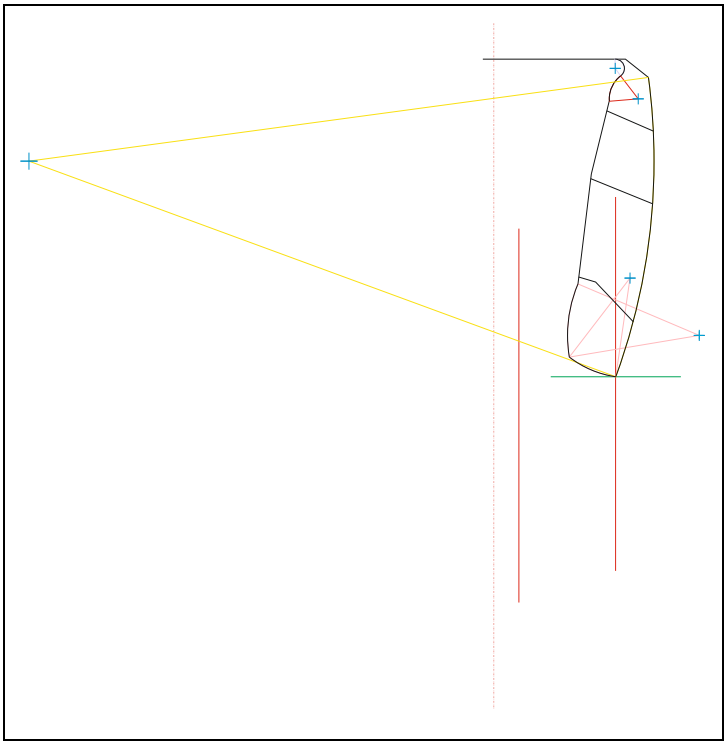


Figure 7.5: Drawing of the restoration outline inverted about the vertical axis to match the preliminary model

The restoration outline was captured through adding points to each line and curve of the restoration's outline. Two points were added for the line and three points for the curved area (Figure 7.6). The co-ordinates of all points of the restoration outline were numbered from 1 to 25 in a clockwise direction. The points for the tooth structure and the dental plaster were numbered with letters from (A) at the root area following the dentine outline, enamel outline to U at the dental plaster outline. All of the co-ordinate points are given in Table 7.2.

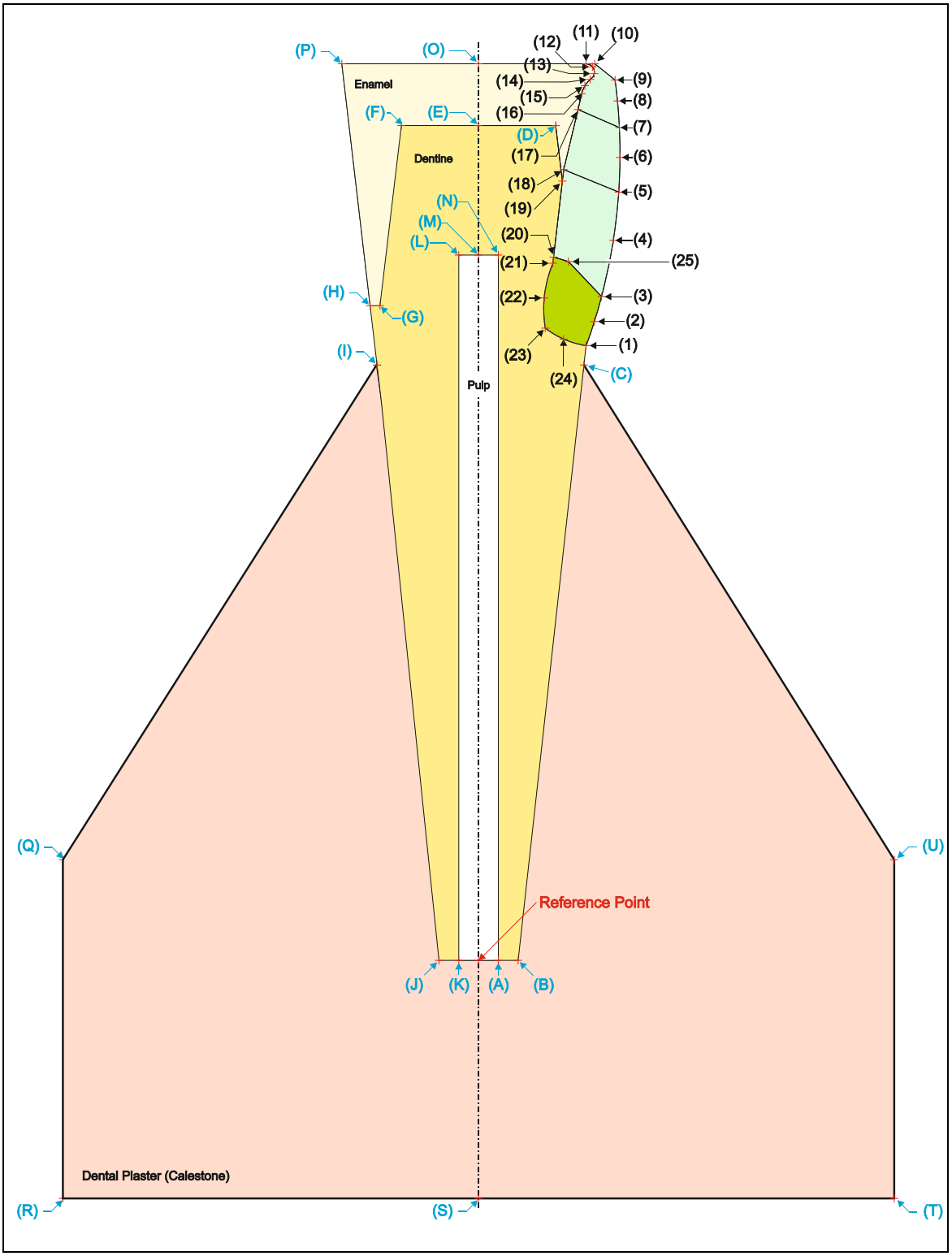


Figure 7.6: Preliminary restoration model

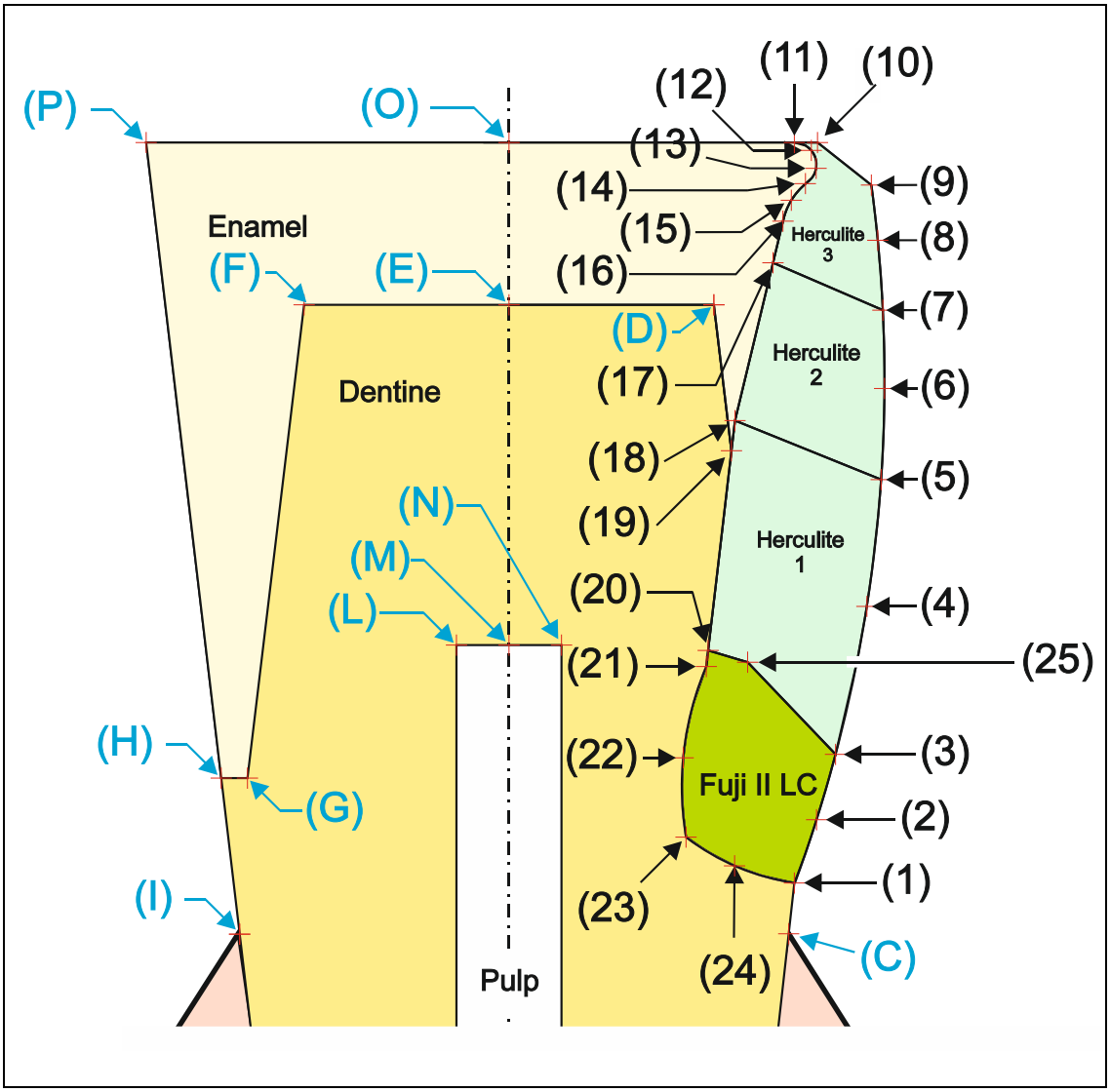


Figure 7.7: Details of the restoration section

Table 7.2: Coordinates of all points in the preliminary restoration model

	Number	x_{True} (mm)	y_{True} (mm)
Tooth section	A	0.5	0
	B	1	0
	C	2.6616	14.942
	D	1.95	20.95
	E	0	20.95
	F	-1.95	20.95
	G	-2.4893	16.4289
	H	-2.739	16.4289
	I	-2.5638	14.938
	J	-1	0
	K	-0.5	0
	L	-0.5	17.7
	M	0	17.7
	N	0.5	17.7
	O	0	22.5
	P	-3.4533	22.5
	Q	-10.5	2.5264
	R	-10.5	-5.9736
	S	0	-5.9736
	T	10.5	-5.9736
	U	10.5	2.5264
Restoration	1	2.7155	15.4271
	2	2.9269	16.032
	3	3.108	16.6558
	4	3.4055	18.0694
	5	3.5415	19.2801
	6	3.5736	20.1517
	7	3.5578	20.899
	8	3.5095	21.5671
	9	3.4485	22.0944
	10	2.9357	22.5
	11	2.7157	22.5
	12	2.8762	22.4254
	13	2.9227	22.2541

14	2.8208	22.108
15	2.6863	21.9492
16	2.607	21.7488
17	2.5121	21.3526
18	2.1506	19.8443
19	2.117	19.5559
20	1.895	17.6492
21	1.8777	17.4949
22	1.6577	16.6236
23	1.6844	15.8653
24	2.1463	15.5917
25	2.271	17.5366

7.3 Process of generating complete/anatomical model:

The final model shape was created to include the detailed features of the tooth structure and the restorations. The plan was to create a model for each premolar tooth (two maxillary and the two mandibular) and superimpose the relative restoration outline from the tooth sections photographs to the created model.

The external shape of the all four premolar teeth was generated using the shape and size definition from Nelson and Ash (2010). The process of doing this required the following 37 steps (Figure 7.8):

1. The sketch of the tooth from Nelson and Ash (2010) was scanned, imported into CorelDraw and proportionally scaled until it had a vertical dimension of approximately 250 mm. This size was scaled by a factor of 10 to allow for approximately 26 sections to be inserted.

2. Starting with the top of the tooth, lines at approximately 10mm spacing were drawn all the way down to the bottom of the tooth. If there were regions in the tooth where its curvature changed considerably between each line, further lines were added to capture the change in curvature.

3. At the intersection of these horizontal lines and the outer boundary of the tooth, a point was defined by placing a cross over the intersection.

4. Two rough spline curves were drawn, one around the enamel, and the other around the dentine. The starting point of each spline was placed on the left enamel/dentine boundary. A new control point was added on each spline curve where each point defined in step 3 was located. The gradient of each generated point was altered so that the spline followed the contour of the tooth.

5. The outline of the tooth was then scaled horizontally so that the mesio-distal diameter of the crown matched the dimension specified in Nelson and Ash (2010). The outline was then stretched vertically so that the vertical length of the tooth matched the sum of the length of the crown and root given in Nelson and Ash (2010). The outline was stretched so that the drawing of the tooth has a scale factor of 10 compared to a real tooth. (At times, it was necessary to shift the crosses inwards so that the drawn outer boundaries matched the outer bounds of the tooth, making it easy to then scale it to the right size).

6. Although the cemento-enamel junction (CEJ) should be specified according to the measurements found in Nelson and Ash (2010), their specified location is based on an average calculation. Therefore, it was

extremely hard to match it exactly to an individual tooth. Hence, the photograph of the restored tooth was superimposed below the tooth boundary and scaled to fit as closely as possible within the dimensions of the tooth boundary.

7. The location of the start of the restoration was defined on the tooth outline.
8. The start of the restoration was always created 1 mm below the CEJ (Stockton and Tsang, 2007; Loguercio et al., 2002). Hence a line 1 mm above the start of the restoration was drawn to define the CEJ.
9. All horizontal lines were removed from the model, apart from the CEJ line.
10. Based on the work of Shillingburg and Grace (1973), horizontal lines above and below the CEJ were drawn at the specific locations where the enamel and dentine thicknesses were measured.
11. Extra points were added on the tooth surface where these new horizontal lines intersect the surface of the tooth.
12. Based on the measurements taken by Shillingburg and Grace (1973) (Appendix B.1), these points were shifted inwards from the surface of the tooth to define the enamel/dentine boundary and also the dentine/pulp boundary.
13. All remaining horizontal and vertical construction lines in the drawing were removed, only the CEJ line was left.
14. Since the tooth restorations were done on either the mesial or distal sides, both the upper boundary of the general tooth and of the

enamel/dentine boundary did not coincide with that of the restored tooth. To correct for this difference, vertical lines were drawn through each of the control points on the upper boundary of the tooth and also from those points generated in step 12 where the dentine/enamel boundary differed from that of the photograph. Adding more lines was necessary to capture the new tooth upper boundary and that of the enamel/dentine boundary.

15. The boundary points were moved to match the upper boundary of the photograph of the tooth, extra ones was added as necessary.

16. The spline control points were moved from the upper boundary onto these points, making certain that the tooth boundary closely matched the photograph. New control points were added as necessary.

17. Points were added along the enamel/dentine boundary where the photograph matched the vertical lines drawn in step 14.

18. All vertical lines were removed.

19. A spline was drawn going through each of the control points which defined the enamel/dentine boundary.

20. For any control point in the dentine/pulp boundary defined in step 12 which did not match the pulp boundary of the photograph, these control points were shifted to match the photograph.

21. A spline was then drawn going through each of the control points to define the dentine/pulp boundary.

22. Over the restoration smooth curves were traced and defined the boundary between the Herculite and Fuji.

23. The scaled photograph was removed; all spline lines were turned to black and the restoration lines to another visible colour (i.e. green).
24. New points were generated where the boundary of the tooth intersected the restoration (On the enamel and dentine).
25. The enamel and dentine boundaries which were overlapped by the restoration were removed. Thus leaving the tooth and its restoration.
26. Sufficient extra points were added on the boundary of the restoration section to be able to represent it with splines (2 points for straight line, 3 or 4 points for curves).
27. A horizontal line 1 mm below the CEJ was added, to define the beginning of the plaster base used to encase the tooth.
28. Two points where this line intersected the tooth boundary were defined. Then a point half way between these two points was added.
29. A vertical line through this new point was drawn to define a vertical symmetry-line of the tooth.
30. Two horizontal lines were drawn, one 10 mm and the other 17 mm below the line generated in step 27.
31. Two copies of the vertical central line generated in step 29, one 10.5 mm to its left and the other 10.5 mm to its right.
32. The two lines drawn in step 30 were extended to the two vertical lines drawn in step 31.
33. From the two points drawn in step 28 lines were drawn to the upper two points from the connections of step 32.

34. The two vertical lines from step 29 were shrunk to the extreme of step 33.
35. The line drawn 10 mm below the line generated in step 27 and the horizontal line drawn in step 27 were deleted.
36. The coordinates of all of the points defining the plaster, dentine, enamel and restoration could then be extracted. For ease of finding the coordinates, it is preferable to name all enamel points with the prefix E, all dentine points with the prefix D, all restoration points with the prefix R and all plaster points with the prefix P.
37. The coordinates of all points were extracted (Appendix B.2,).

The teeth that were numerically represented were the:

1. Mandibular 1st Premolar (Figure 7.8a)
2. Mandibular 2nd Premolar (Figure 7.8b)
3. Maxillary 1st Premolar (Figure 7.8c)
4. Maxillary 2nd Premolar (Figure 7.8d)

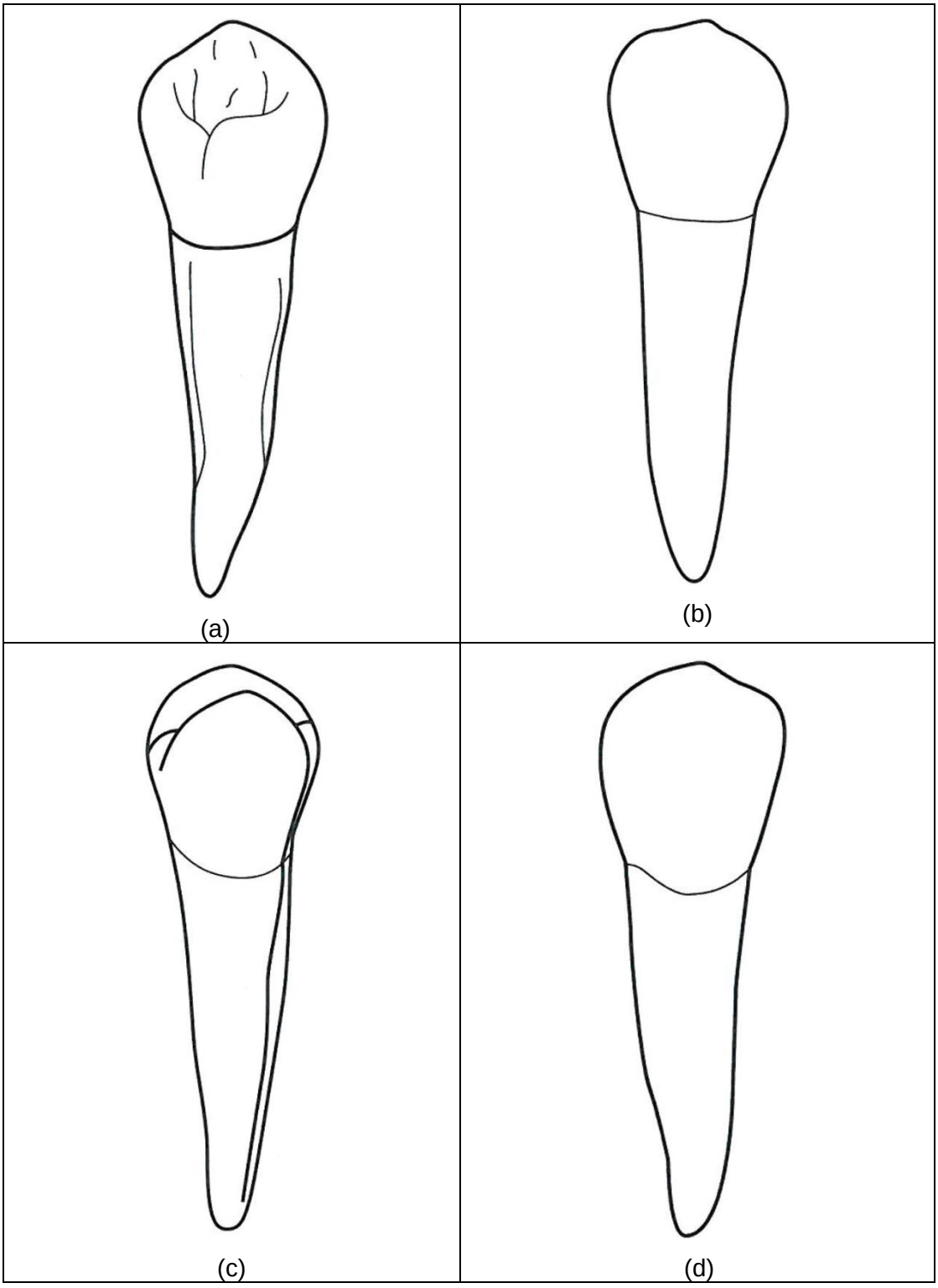
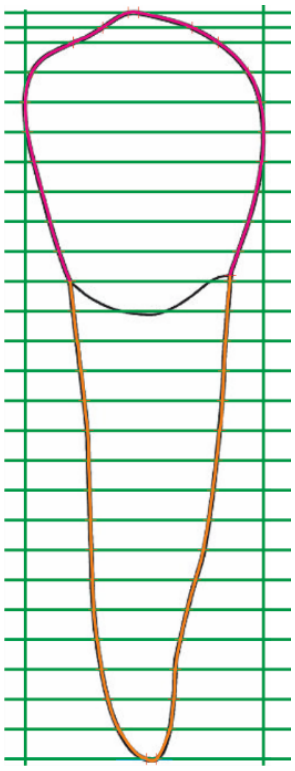
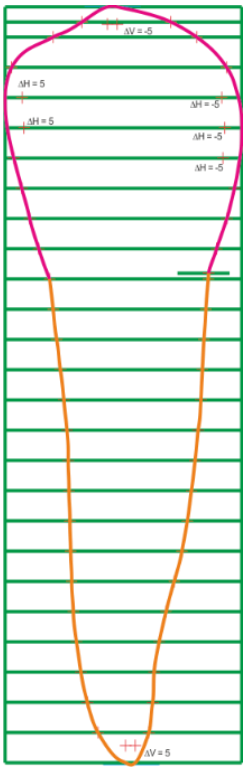


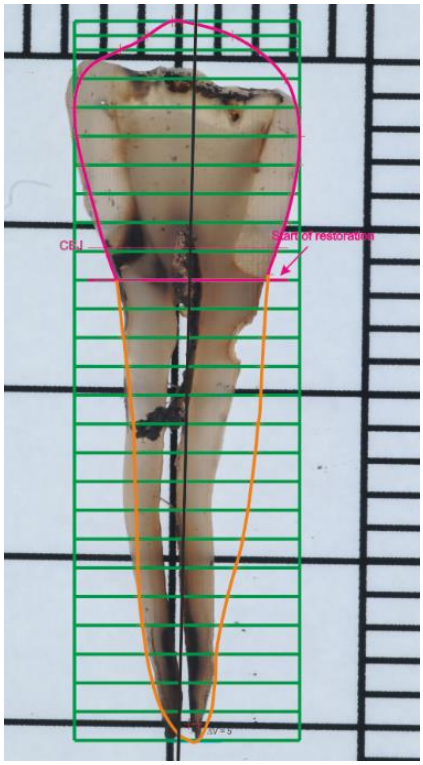
Figure 7.8: (a) Mandibular 1st Premolar, (b) Mandibular 2nd premolar, (c) Maxillary 1st premolar and (d) Maxillary 2nd premolar: external shape definition, Nelson and Ash (2010).



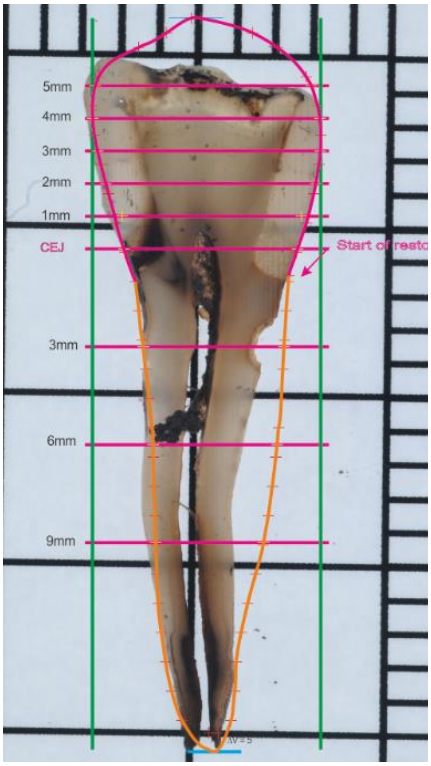
Steps 1,2,3



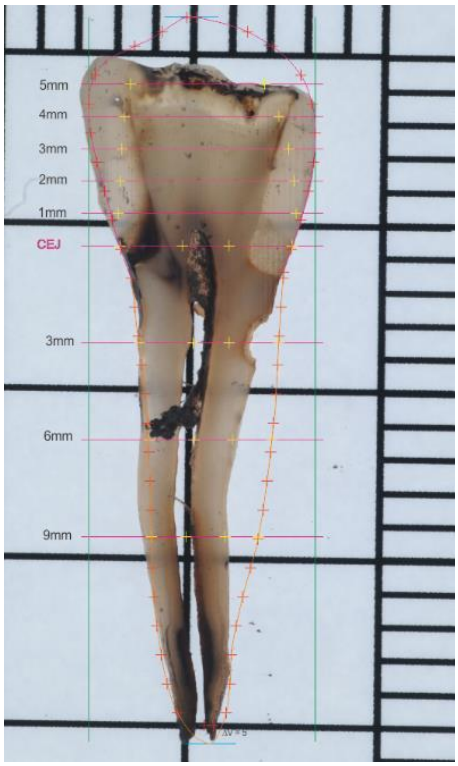
step 4



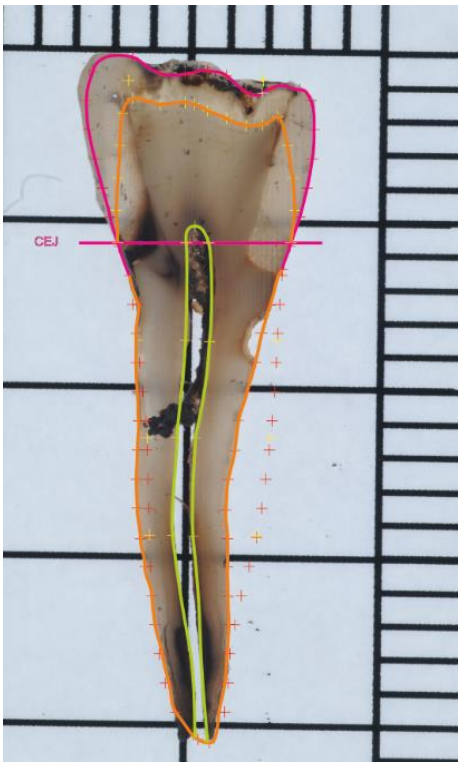
steps 5,6,7,8



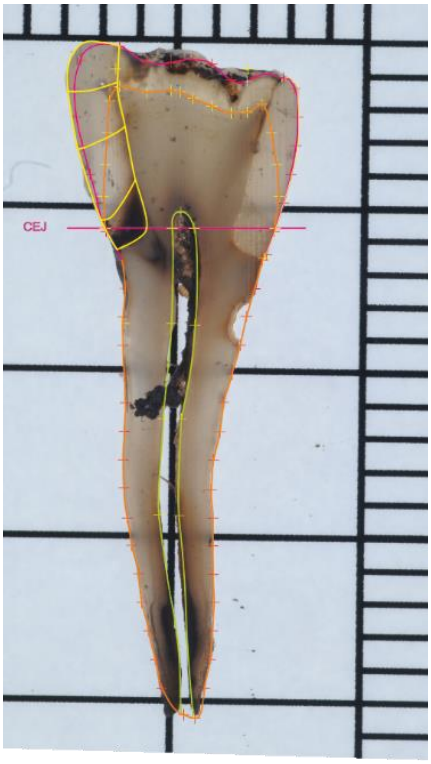
Steps 9,10,11



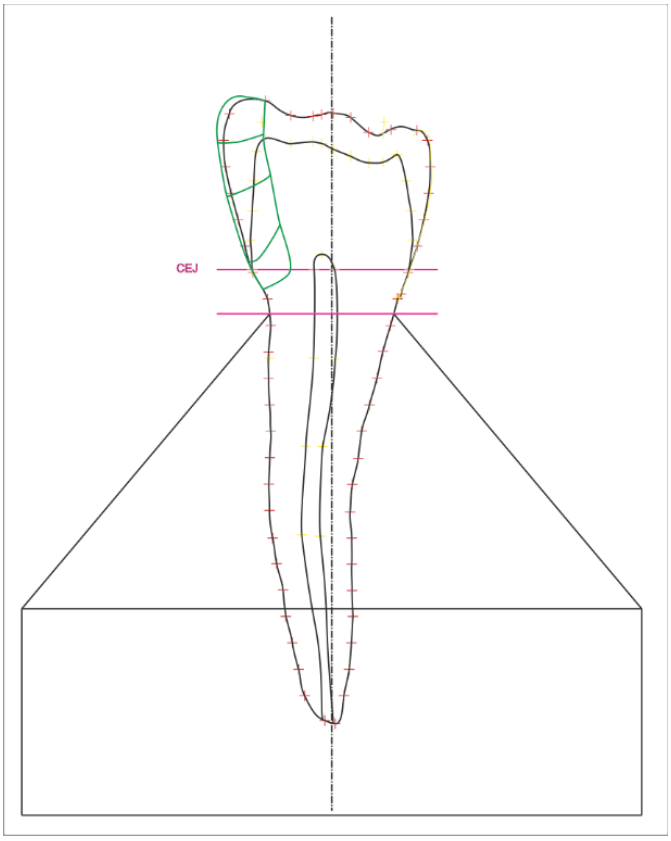
Step 12



Steps 13,14,15,16,17,18,19,20,21



Step 22



Steps 23,24,25,26,27,28,29,30,31, 32, 33, 34,35

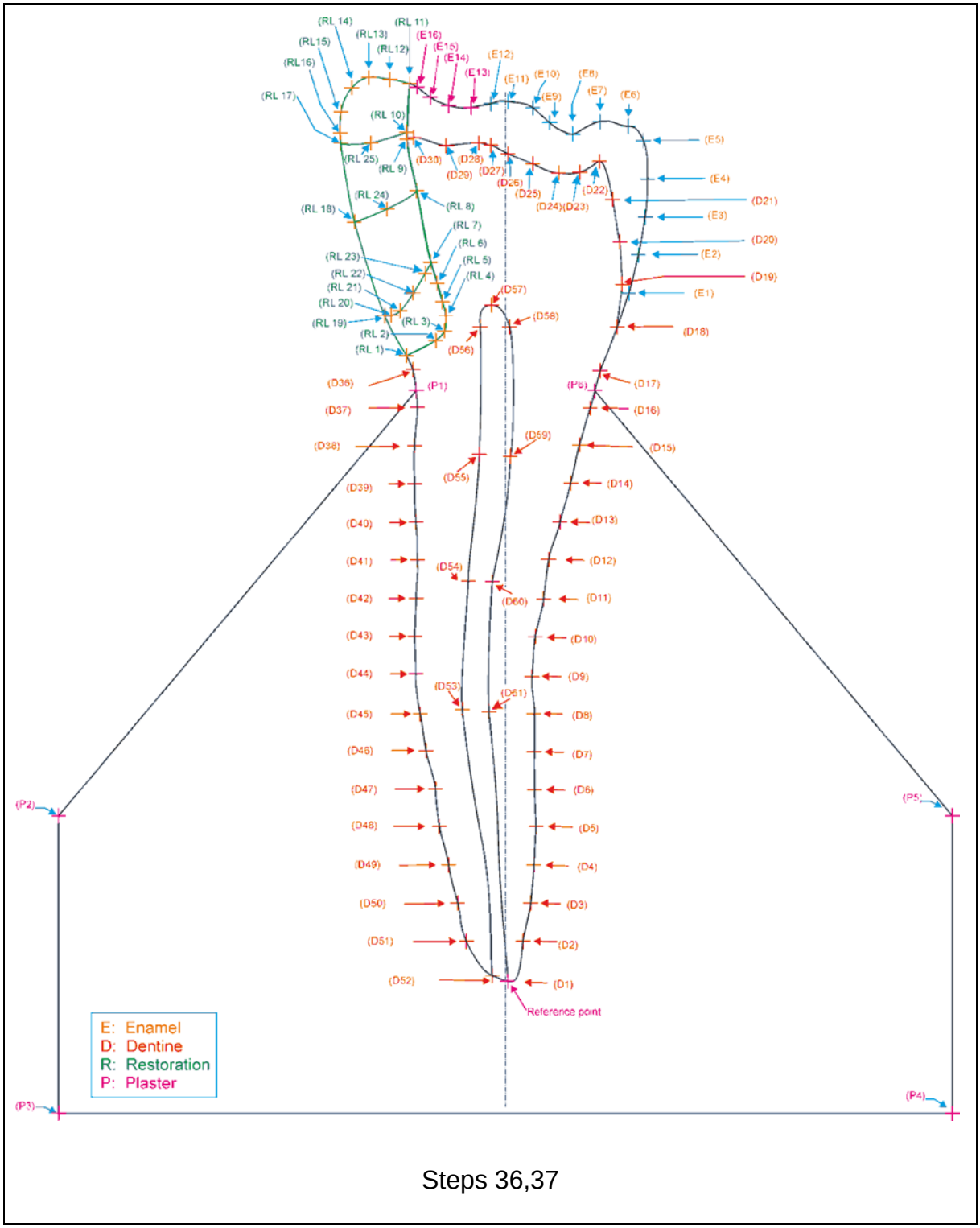


Figure 7.9: Different steps of model generation

Following all the previously mentioned steps an idealised model of the tooth was generated as shown in Figure 7.10. The model was then used for the finite element analysis.

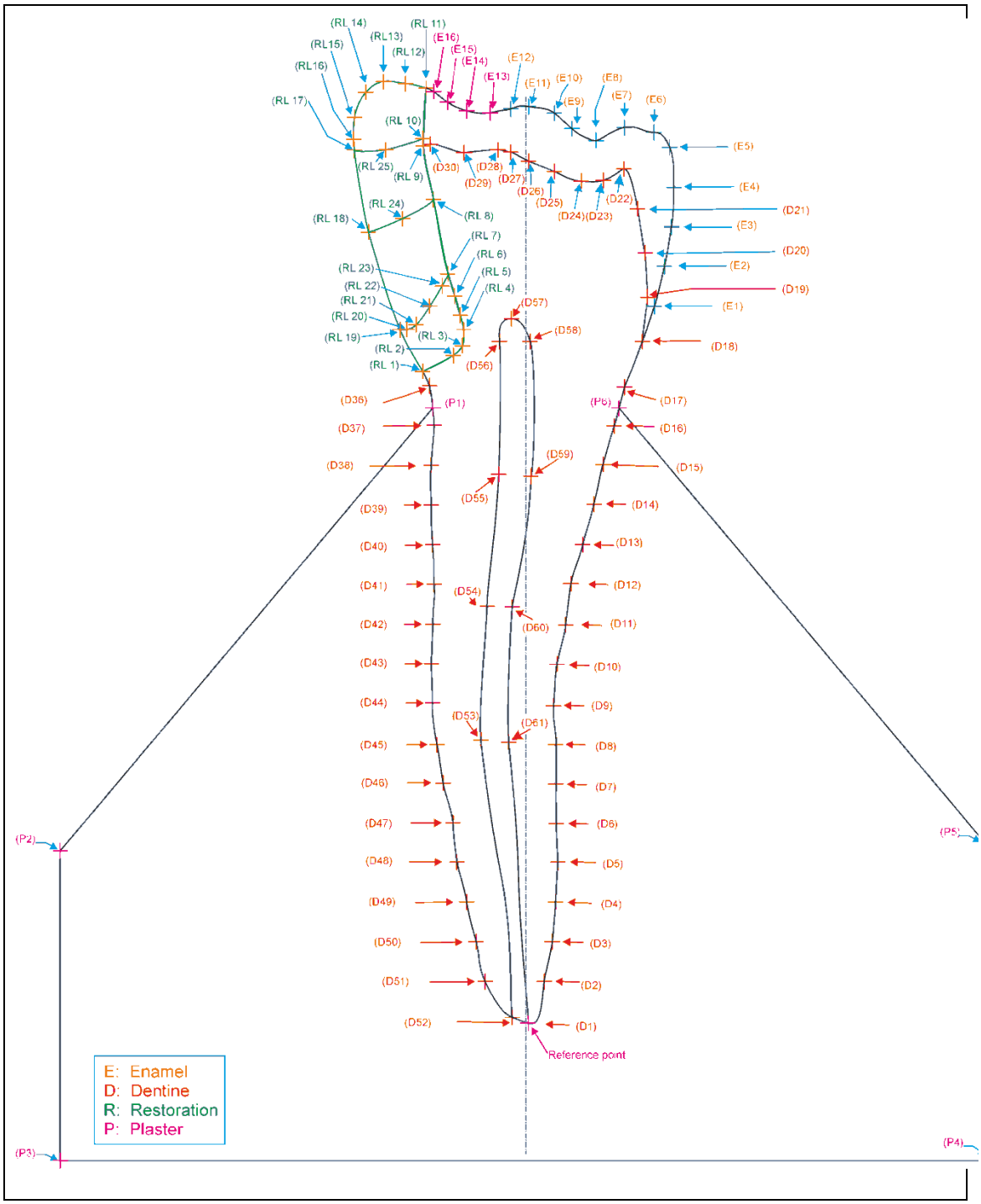


Figure 7.10: Complete/ anatomical model of the Maxillary 2nd premolar tooth with only one restoration section

The details of the upper part of the idealised model of maxillary 2nd premolar was presented in Figure 7.11 and that for the lower part of the tooth idealised model was presented in Figure 7.12.

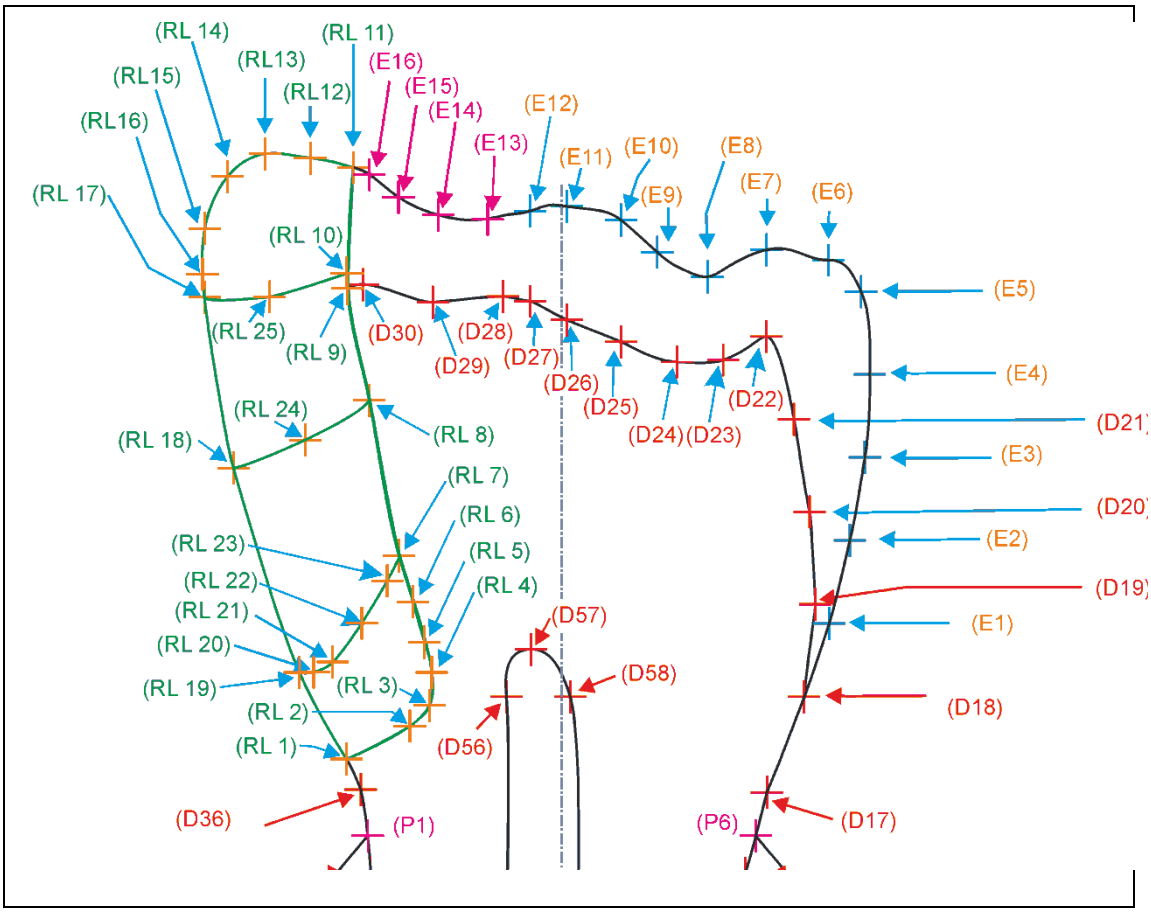


Figure 7.11: Detail of the Maxillary 2nd premolar tooth model – Upper half

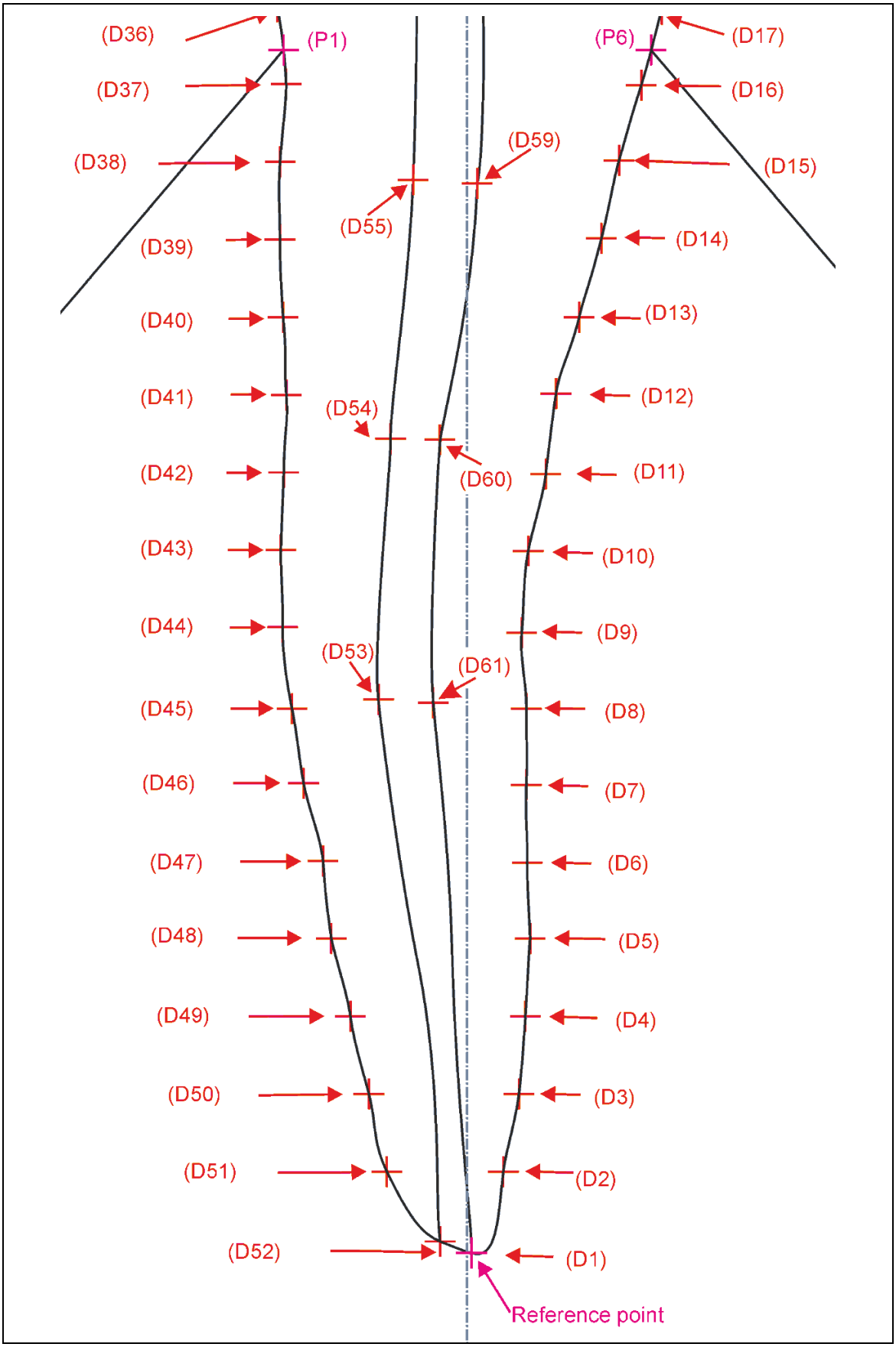


Figure 7.12: Detail of the Maxillary 2nd premolar tooth model – Lower half

To conclude, development of numerical model for the current study was started with preliminary model which had been de-featurized in order to simplify the model and obtain a preliminary result, the model include the detailed restoration outline as shown in Figure 7.6 and finally generate the complete/aatomical model including all of the tooth and restoration outlines details as shown in Figure 7.10.

The models in this study were analyses using the software tool COMSOL (2015). The finite element meshes were generated using Physics-Controlled meshes using Normal finite element size, which generated models with between 24,000 and 32,000 degrees of freedom.

Chapter 8

Finite element analysis and the assessment of the stress generated in sandwich restoration

8.1 Introduction

As a first assumption; from the previous literature review; the material properties for the resin based materials was interpreted to be linear static and at no time where they ever elasto-plastic in nature, thus deforming plastically with no change in the stress level of the physical domain. The articles by Hübsch et al (2000), Dauvillier et al (2000, 2003), Barink et al (2003), Koplin et al (2008; 2009) clearly demonstrated that the properties of the resin based material exhibited viscoelastic behaviour during the curing shrinking stage of these resins.

Such behaviour means that the original linear static analysis which was planned to be carried out with the finite element analysis for this study was technically incorrect and that a new way of running the analysis is required. Although a viscoelastic model would be the ideal model to use, looking at the way that the material behaves, a simplification of the behaviour can be constructed using a linear static model using different properties at different stages of the curing process. Since the idea of this analysis is to provide an indication of the effect of the curing process on the microleakage of sandwich restoration using resin based material, as long as the model shows the regions of where high stresses may be induced, this would be an appropriate first step in isolating the regions of high stresses and also looking at possible changes in the shape/ type of filling process to minimise any unduly high stress regions of the restorations. It

is of course noted that to obtain accurate stress values, a viscoelastic model should be used. But that was deemed inappropriate complicated and limitations in the available time meant that only-linear static analysis could be performed.

According to the literature review, there were no previous researches considered analysing stress distribution around resin composite sandwich restorations using Finite element Analysis.

8.2 Aim

The aim of this chapter was to investigate the stress distribution in the open sandwich restorations using resin modified glass ionomer cement (RMGIC) when curing the two materials together or separately.

8.3 Objective

Finite Element Analysis was used to analyse the stresses within the tooth structure in order to detect the areas of high stress, which could be more susceptible to gap formation and microleakage in sandwich restorations .this was achieved by a two step analysis. Firstly, using a preliminary resstoration model (7.6) and secondly a more complete/ anatomical model (7.10).

8.4 Methods

With the purpose of analysing stress in the resin composite sandwich restoration, tooth model was generated as explained in Chapter 7. Further more, to acomplish the FEA, it was necessary to imitate the volumetric shrinkage of the restorative materials.

The actual shrinkage of the specimens was generated by using an artificial thermal load. The first step was to find the temperatures that could be applied to the restoration to get the specified volumetric shrinkage in the literature review for the restorative materials which include; the resin composite (Herculite) and the resin modified glass ionomer cement (Fuji II LC).

Since the analysis carried out in this study was 2D, rather than 3D, the volumetric shrinkage for the Herculite and Fuji II cement was converted from volumetric to area shrinkage. Assuming that there was a linear change in the length of the specimen denoted by the symbol s_L, then the change in the area, Figure 8.1, and volume are given below:

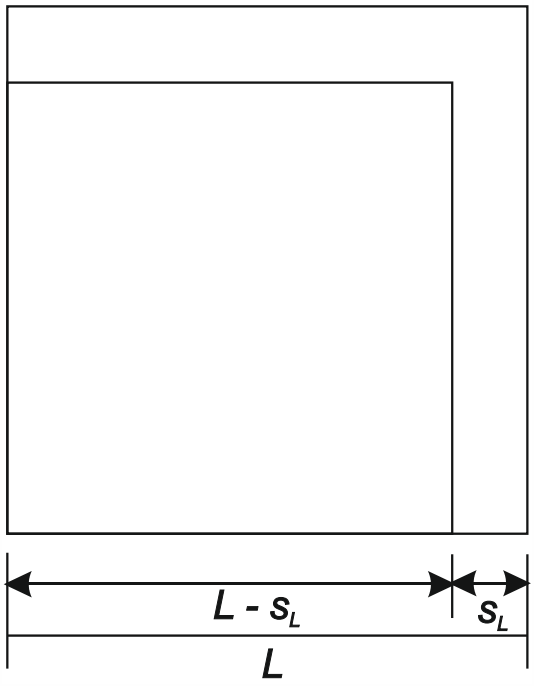


Figure 8.1: Square element showing linear and area shrinkage

8.5 Calculating area shrinkage

The original area is defined as:

$$A_0 = L^2$$

The area after a linear reduction in the length of both sides is defined as:

$$A_1 = \left(L - s_L\right)^2$$
$$A_1 = L^2 - 2s_L + s_L^2$$

The overall area reduction given by:

$$\Delta A = A_0 - A_1$$
$$\Delta A = L^2 - \left(L^2 - 2Ls_L + s_L^2\right)$$
$$\Delta A = 2Ls_L - s_L^2$$

And the area shrinkage is then given by:

$$\frac{\Delta A}{A} = \frac{A_0 - A_1}{A_0}$$
$$\frac{\Delta A}{A} = \frac{2Ls_L - s_L^2}{L^2}$$

8.6 Calculating volume shrinkage:

The original volume is defined as:

$$V_0 = L^3$$

The volume after a linear reduction in the length of the three sides is defined as:

$$V_1 = (L - s_L)^3$$
$$V_1 = L^3 - 3L^2 s_L + 3L s_L^2 - s_L^3$$

The overall volume reduction is given by:

$$\Delta V = V_0 - V_1$$
$$\Delta V = L^3 - \left(L^3 - 3L^2 s_L + 3L s_L^2 - s_L^3\right)$$
$$\Delta V = 3L^2 s_L - 3L s_L^2 + s_L^3$$

And the volume shrinkage is then given by:

$$\frac{\Delta V}{V} = \frac{V_0 - V_1}{V_0}$$
$$\frac{\Delta V}{V} = \frac{3L^2 s_L - 3L s_L^2 + s_L^3}{L^3}$$

The Volumetric shrinkage ($\Delta V/V$) % for Resin composite Herculite XRV is 2.73±0.31% and for Glass Ionomer Cement, Fuji II LC is 2.53 %.

The corresponding linear and area reductions required to produce the 2.73% and 2.53% volumetric shrink are given in Table 8.1:

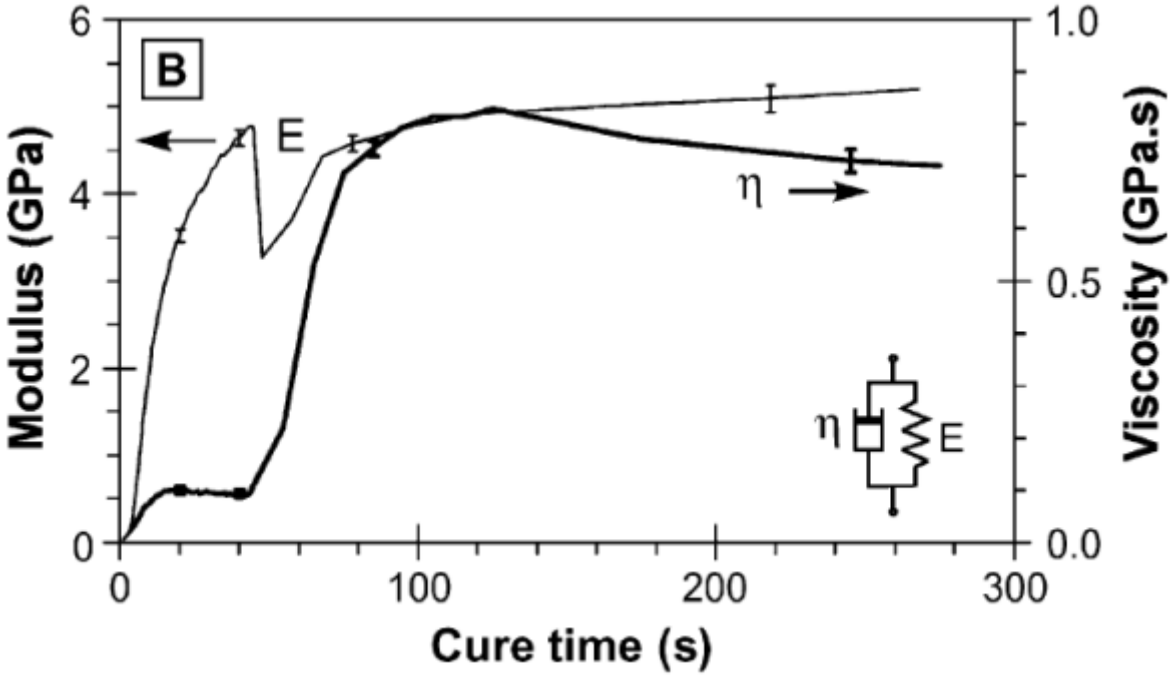
Table 8.1: Linear and area volume changes to produce the required volume changes for Fuji and Herculite

	L	**ΔL**	**ΔL/L %**	**A**	**ΔA**	**ΔA/A %**	**V**	**ΔV**	**ΔV/V %**
Fuji	1	0.0085	0.85	1	0.017	1.69	1	0.025	2.53
Herculite	1	0.0091	0.92	1	0.018	1.82	1	0.027	2.73

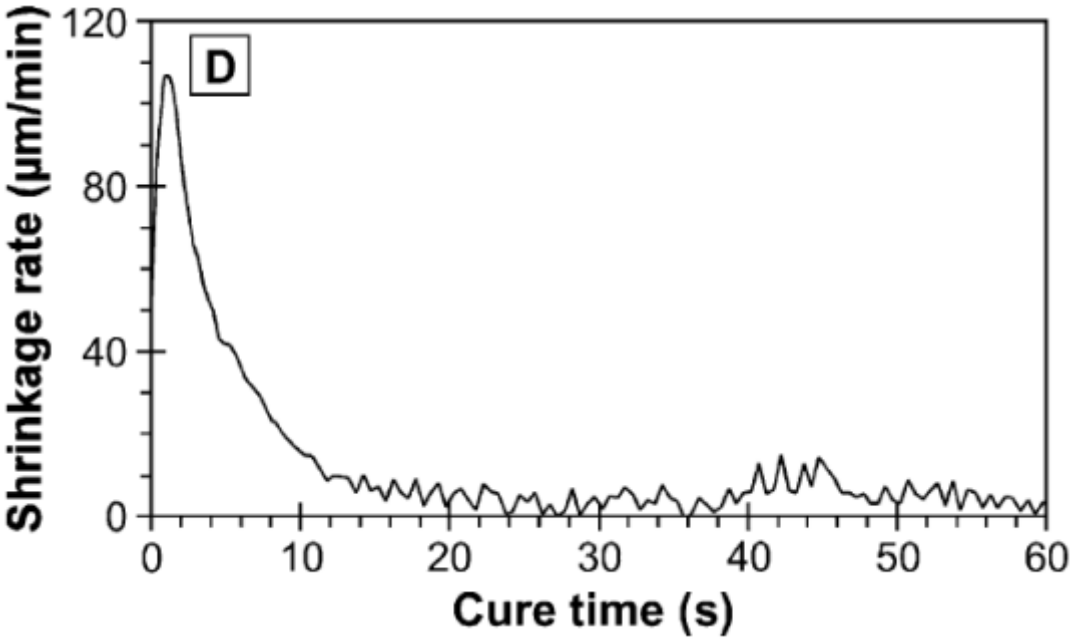
In order to determine the amount of shrinkage for which there is no stress generated, the paper by Dauvillier et al. (2003) was analysed as it provided the linear shrinkage rate for a light activated resin. The material used in that study had different properties than both the Fuji and Herculite materials, but as detailed material properties for Fuji and Herculite are not available to the depth as specified by Dauvillier et al. (2003), several assumptions had to be made in order to carry out the stress analysis of the cured Fuji and Herculite. These were that:

1. Both the Fuji and Herculite material exhibit a viscoelastic behaviour similar to that of Z100 MP A3, and hence by examining the % linear shrinkage change and % Young's modulus change with time for Z100, the same % changes for both Fuji and Herculite could be extrapolated;
2. The discrepancy between the measured maximum Young Modulus and that reported by the manufacturer are proportional for Fuji and Herculite as was the case for Z100 (Dauvillier et al., 2003), where only 50% of the reported Young's modulus was measured 1 hour after curing.
3. Although in Figure 8.2(a) there was a dip in the Young's modulus between the 40 and 100 second gap, for the purpose of this analysis it was assumed that this dip wasn't present and instead that the Young's modulus value increases gradually up to its 50% level after 1 hour.

Both images in figures 8.2 (a, b) were analysed, and the data from these two curves were extracted to produce the actual shrinkage rates and Young Modulus values at the different curing times.



(a)



(b)

Figure 8.2: Standard linear solid model and shrinkage rate diagram showing how the properties vary with time Dauvillier *et al* (2003)

Dauvillier et al. (2003) stated that "*the material undergoes 15% of the measured axial shrinkage strain without generating shrinkage stress*."

Although the analysis should consider the viscoelastic effect of the material, a step wise approach was used in this study. Since the properties of Fuji and Herculite are comparable with those of Z100, the % variation of Z100 was used to estimate the % variation of both the shrinkage rate and Young's modulus of Fuji and Herculite. Figure 8.3, shows the % variation of Z100.

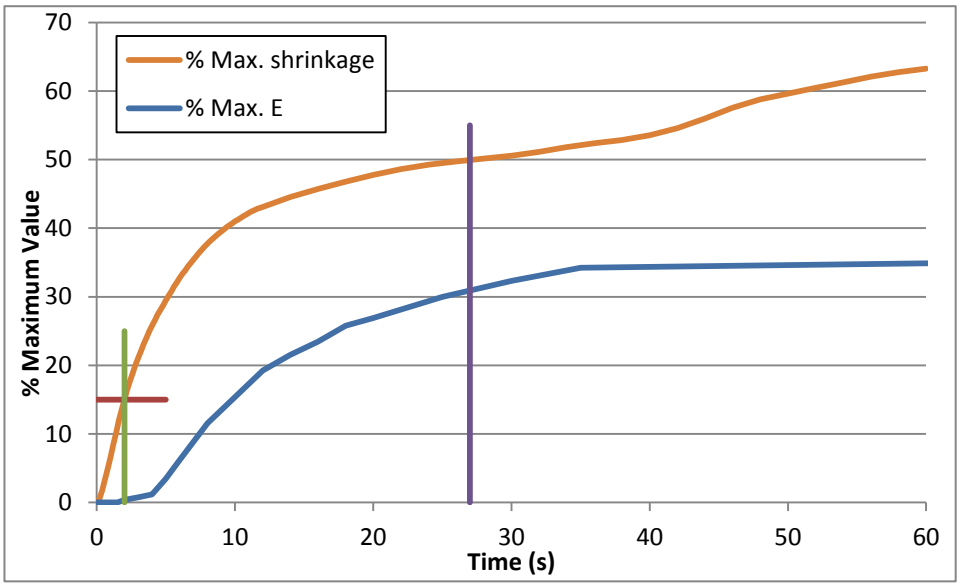


Figure 8.3: Percentage (%) variation of material and shrinkage properties of Z100

Dauvillier et al. (2003) also stated that "*The Young's modulus (E) after 1h curing (approximately 6.5 GPa) is not in agreement with the value of 13 GPs provided by the manufacturer.*" For this reason, it was assumed that the highest Young's modulus achievable within a 1 hour period was 50% of that suggested by manufacturers.

8.7 The step-wise analysis

The analysis carried out was as follows:

1. For the first 2 seconds, the first 15% of shrinkage does not seem to generate any stresses, then disregard this amount of shrinkage for both

Fuji and Herculite. As the actual displacement of the tooth restoration is negligibly small, there is no need; to analyse it and determine the variation in the surface of the restoration. As such small changes in the geometry will not have any measurable effect in the stress generation.

2. For the next 25 seconds, a further 35% of the shrinkage takes place. Although the Young's modulus varies during this time, an average young's modulus was calculated by determining the area under the %E graph between t = 2s and t = 27s and divided by 25s to give that the average %E = 23%. So this value was used to calculate the 35% of shrinkage.
3. For the remaining 50% of shrinkage, the same averaging process of the Young's modulus was used, and up to the 1 hr time limit as specified by Dauvillier et al. (2003), the average %E = 44%.
4. So, only 2 linear elastic analysis were required to be carried out:
    a. 35% shrinkage with E = 23% of manufacturer given value
    b. Further 50% shrinkage with E = 44% of manufacturer given value

From the material properties of Table 7.1 and the equivalent linear shrinkage rates for the required volumetric shrinkage rates as given in Table 8.1, the required properties for Fuji and Herculite used in the FEA were extracted and presented in Table 8.2.

Table 8.2: Properties for the restorative material

	Material	Max. E (GPa)	Max. Linear shrinkage (ΔL/L) %	35% shrinkage		50% shrinkage	
				E (GPa)	(ΔL/L) %	E (GPa)	(ΔL/L) %
	Resin composite Herculite XRV [1,9, 10]	9.5	0.91	2.18	0.32	4.18	0.46
	Resin modified Glass Ionomer Cement, Fuji II LC [6]	20	0.85	4.6	0.29	8.8	0.43

Dauvillier et al. (2003) imposed a volume conservation constraint to account for the incompressibility associated with the uncured paste. For this study, no volume constraints were imposed, two models where investigated:

1. Using a Poisson's ratio of 0.49 to simulate volume conservation;
2. Using the Poisson's ratio of Table 7.1 for both materials.

8.8 Determination of Temperatures to simulate 35% of maximum shrinkage:

The model of Figure 8.4 represents a quarter of a square plate of size 2 m which was used to determine the temperature required for both the Herculite and Fuji to shrink by 35% of their maximum shrinkage. The 2D approximation used was plain stress, as it disregards any 3D induced stresses which are present in the plain strain solution.

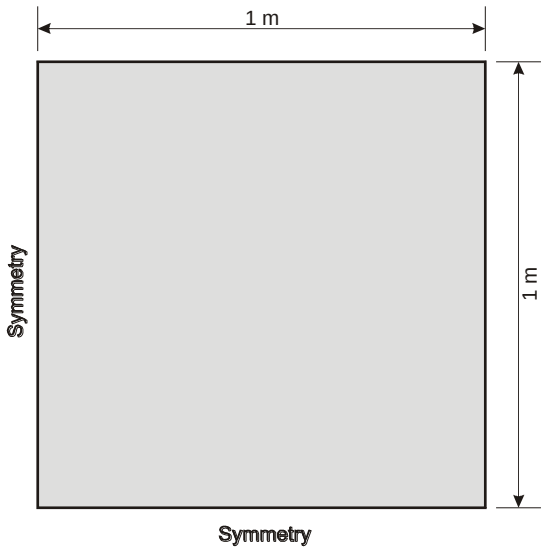


Figure 8.4: Quarter of plate design domain

8.9 Herculite Model Properties and Results

The properties used for the Herculite model are given in Table 8.3.

Table 8.3: Material properties and thermal load for the square plate Herculite Model

Young's Modulus (E)	2.185 GPa
Poisson's' ratio (ν)	0.24
Coefficient of Thermal Expansion (α)	32.6±1.6 x10^{-6} °/K
Density (ρ)	0 kg/m^3
T_{Ref}	0 °K

The results for this numerical experiment are given in Table 8.4 and Figure 8.5.

Table 8.4: Results of temperature shrinkage (35%) numerical experiment for Herculite

T (°C)	(ΔL/L)	(ΔL/L) %	T (°C)	(ΔL/L)	(ΔL/L) %
0	0.0000	0	-110	-0.0036	-0.359
-10	-0.0003	-0.033	-120	-0.0039	-0.391
-20	-0.0006	-0.065	-130	-0.0042	-0.424
-30	-0.0009	-0.098	-140	-0.0045	-0.456
-40	-0.0013	-0.131	-150	-0.0049	-0.489
-50	-0.0016	-0.163	-160	-0.0052	-0.522

-60	-0.0020	-0.196	-170	-0.0055	-0.554
-70	-0.0023	-0.228	-180	-0.0059	-0.587
-80	-0.0026	-0.261	-190	-0.0062	-0.619
-90	-0.0029	-0.293	-200	-0.0065	-0.652
-100	-0.0033	-0.326			

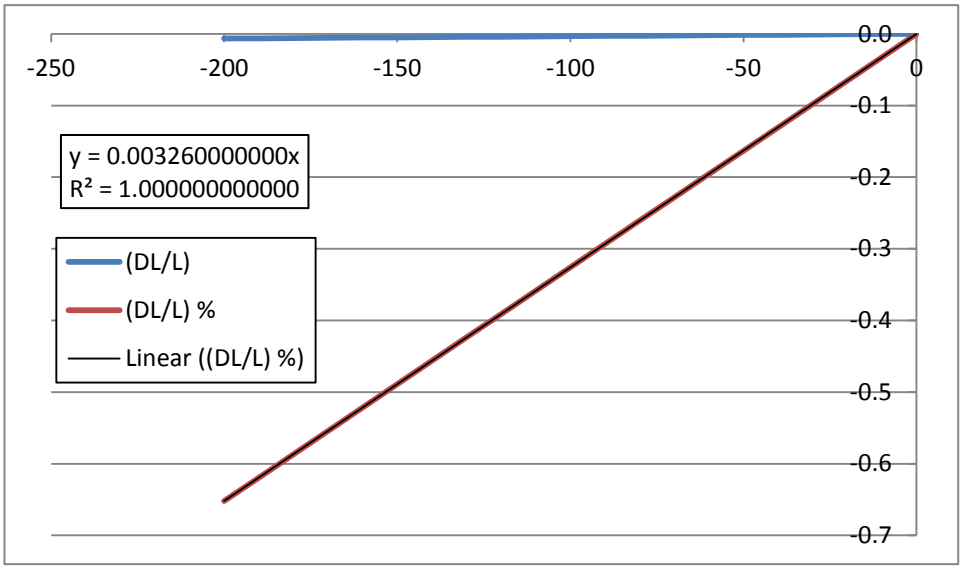


Figure 8.5: Plot of the data from Table 8.4 to determine line of best fit

The line of best fit for this data, as expected is linear, and is given by Eq. (8.1).

$$\left(\frac{\Delta L}{L}\right)\% = 0.00326T \qquad (8.1)$$

Using equation (8.1) and the required shrinkage value for Herculite from Table 8.2, $\left(\frac{\Delta L}{L}\right)\% = 0.322$, this equation can then be rearranged to determine the actual value of the temperature to be applied in order to produce this displacement.

$$-0.3214428 = 0.00326T$$
$$\therefore T = \frac{-0.3214428}{0.00326} = -98.60\ ^{\circ}C \qquad (8.1)$$

The model was re-run with this temperature change, producing the result given in Figures 8.6 and 8.7.

As can be seen from Figure 8.7, the von Mises stress generated in this unconstrained square element was very small to be equivalent to a zero stress field.

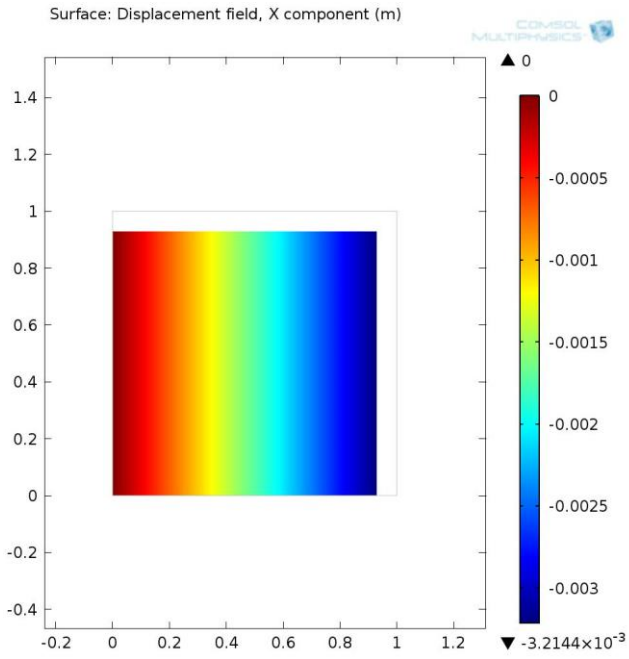


Figure 8.6: Displacement plot showing the displacement due to the -98.60°C temperature applied

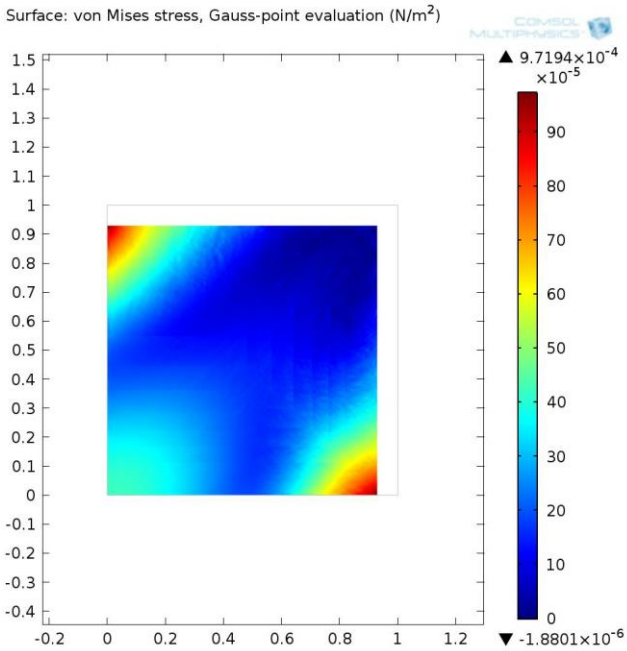


Figure 8.7: von Mises stress plot showing the stresses in (Pa) due to the -98.60°C temperature applied

8.10 Study on the different Poisson's ratio to maintain constant volume due to shrinkage process.

The poison's ration was changed to the maximum value allowable by the programme COMSOL, before it break down. The value is given in Table 8.5. The results are given in Figures 8.8 and 8.9.

Table 8.5: Poisson's ratio for Herculite Model to model constant volume

Poisson's' ratio (ν)	0.49

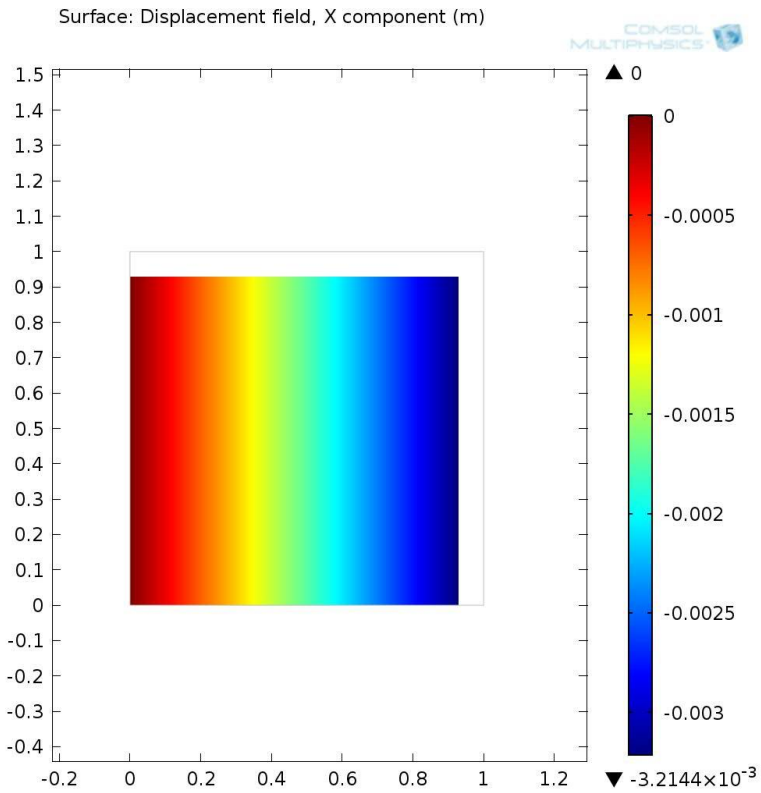


Figure 8.8: Displacement plot showing the displacement due to the -98.60°C temperature applied

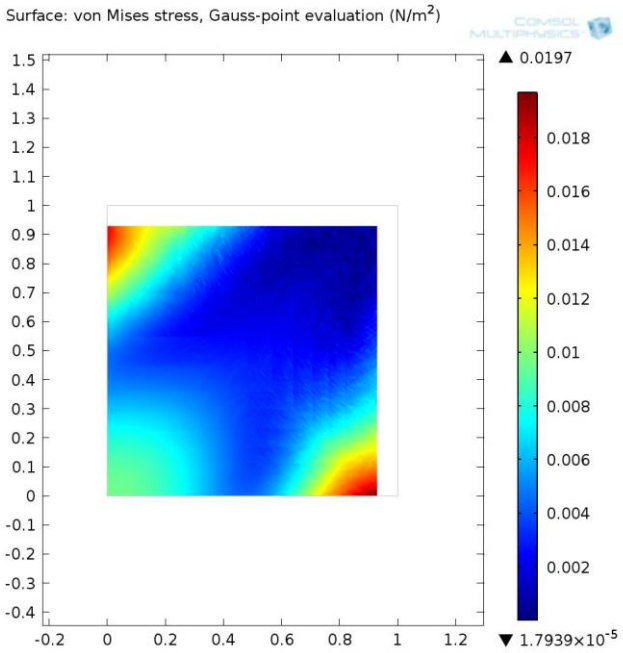


Figure 8.9: von Mises stress plot showing the stresses in (Pa) due to the -98.60°C temperature applied for $\nu = 0.49$

As can be seen from Figures 8.8 and 8.9, there was no effect at all on the temperature which was necessary to provide the required shrinkage, however, a considerable increase in the von Mises stress was noted. Although the maximum stress experienced was 0.0197 Pa, this value was negligibly small.

8.11 Fuji Model Properties and Results

The properties used for the Fuji model are given in Table 8.6.

Table 8.6: Material properties and thermal load for the square plate Fuji Model

Young's Modulus (E)	4.6 GPa
Poisson's' ratio (ν)	0.3
Coefficient of Thermal Expansion (α)	10.8 x10^{-6} °/K
Density (ρ)	0 kg/m^3
T_{Ref}	0 °K

The results for this numerical experiment are given in Table 8.7 and Figure 8.10.

Table 8.7: Results of temperature shrinkage (35%) numerical experiment for Fuji

T (°C)	(ΔL/L)	(ΔL/L) %
0	0.0000	0
-20	-0.0002	-0.02
-40	-0.0004	-0.04
-60	-0.0006	-0.06
-80	-0.0008	-0.09
-100	-0.0011	-0.11
-120	-0.0013	-0.13
-140	-0.0015	-0.15
-160	-0.0017	-0.17
-180	-0.0019	-0.19
-200	-0.0022	-0.21

-220	-0.0024	-0.24
-240	-0.0026	-0.26
-260	-0.0028	-0.28
-280	-0.0030	-0.30
-300	-0.0032	-0.32
-320	-0.0035	-0.35
-340	-0.0037	-0.37
-360	-0.0039	-0.39
-380	-0.0041	-0.41
-400	-0.0043	-0.43

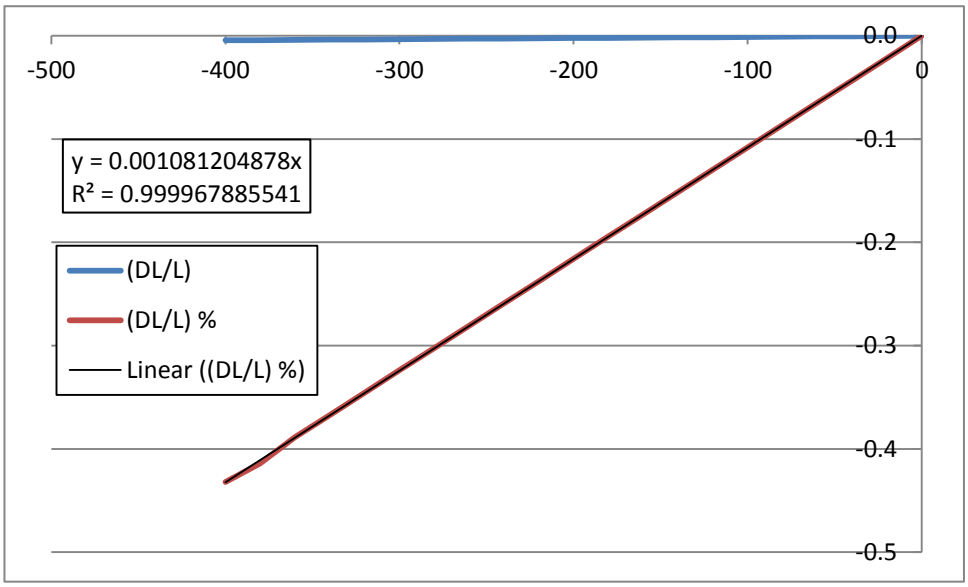


Figure 8.10: Plot of the data from Table 6.7 to determine line of best fit

The line of best fit for this data, as expected is linear, and is given by Eq. (8.2).

$$\left(\frac{\Delta L}{L}\right)\% = 0.001081205T \qquad (8.2)$$

Using equation (8.2) and the required shrinkage value for Fuji from Table 8.2, $\left(\frac{\Delta L}{L}\right)\% = 0.2976911$, this equation can then be rearranged to determine the actual value of the temperature to be applied in order to produce this displacement.

$$-0.2976911 = 0.001081205T$$
$$\therefore T = \frac{-0.2976911}{0.001081205} = -275.333\,°C$$

The model was re-run with this temperature change; however the linear shrinkage value obtained was -0.0029736, which is -0.29736%. This value is 0.11347% too small, so the temperature value should be increased by a factor of 1.00111347, meaning that the temperature should be: T = -275.6396°C. Working shown in equation (8.3)

$$T_{Fraction} = \frac{-0.2976911}{-0.29736} = 1.001113465$$
$$\therefore T_{New} = 1.001113465 \times -275.333 = -275.64\,°C \qquad (8.3)$$

This new slightly increased temperature gave the correct required shrinkage. The results of the analysis are therefore given in Figures 8.11 and 8.12.

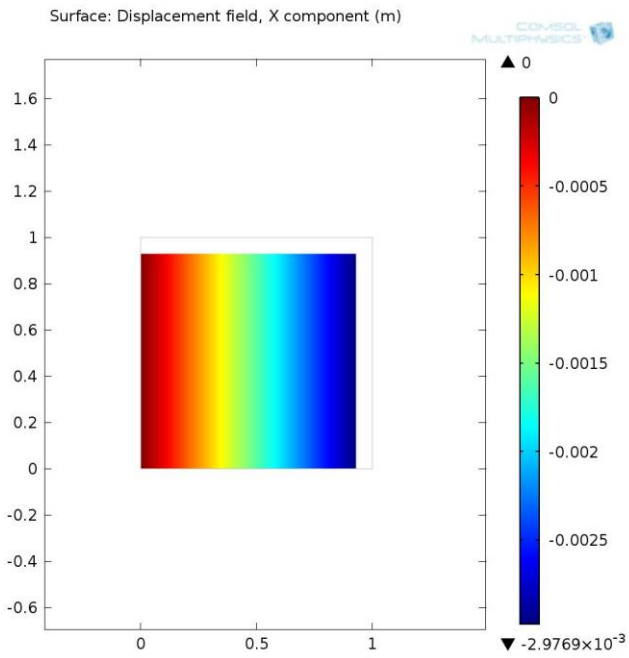


Figure 8.11: Displacement plot showing the displacement due to the -275.64°C temperature applied

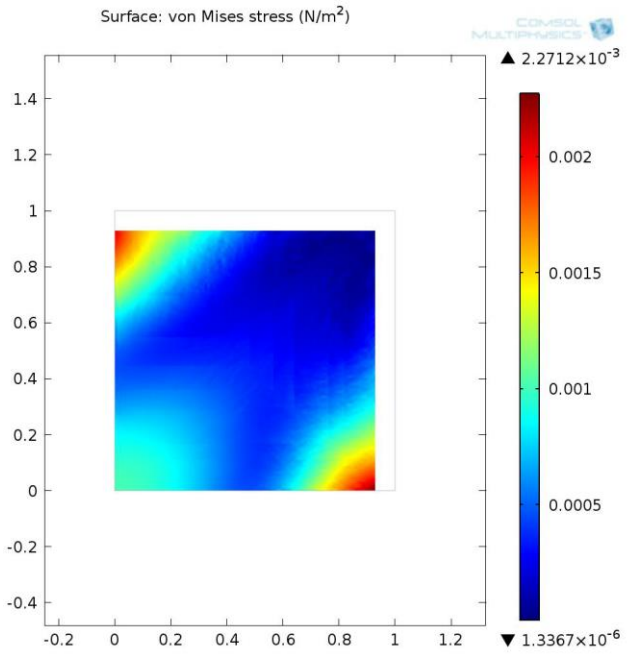


Figure 8.12: von Mises stress plot showing the stresses in (Pa) due to the -275.64°C temperature applied

As can be seen from Figure 8.12, the von Mises stress generated in this unconstrained square element is negligible enough to be equivalent to a zero stress field.

8.12 Study on the different Poisson's ratio to maintain constant volume due to shrinkage process.

The Poisson's ratio was changed to the maximum value allowable by the programme COMSOL, before it break down. The value is given in Table 8.8. The results are given in Figures 8.13 and 8.14.

Table 8.8: Poisson's ratio for Fuji Model to model constant volume

Poisson's' ratio (ν)	0.49

As can be seen from Figures 8.13 and 8.14, there was no effect at all on the temperature which was necessary to provide the required shrinkage, there was however, a considerable increase in the von Mises stress. Although the maximum stress experienced was 0.0374 Pa, this value was negligible small.

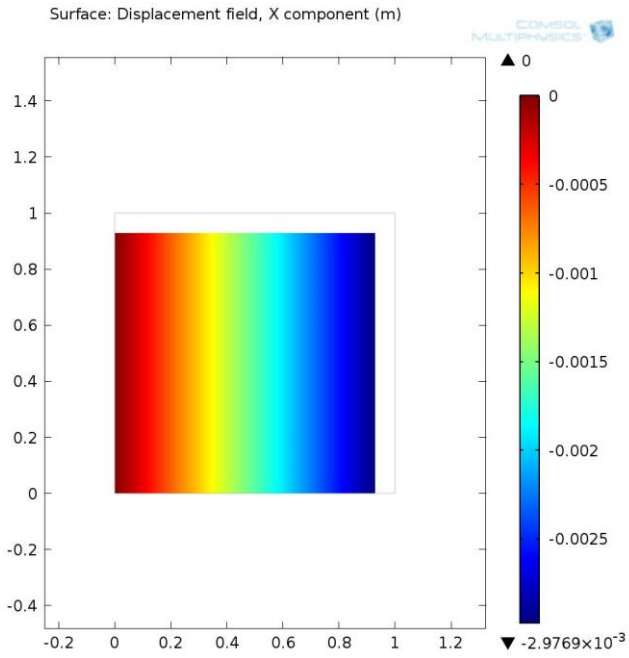


Figure 8.13: Displacement plot showing the displacement due to the -275.64°C temperature applied for ν = 0.49

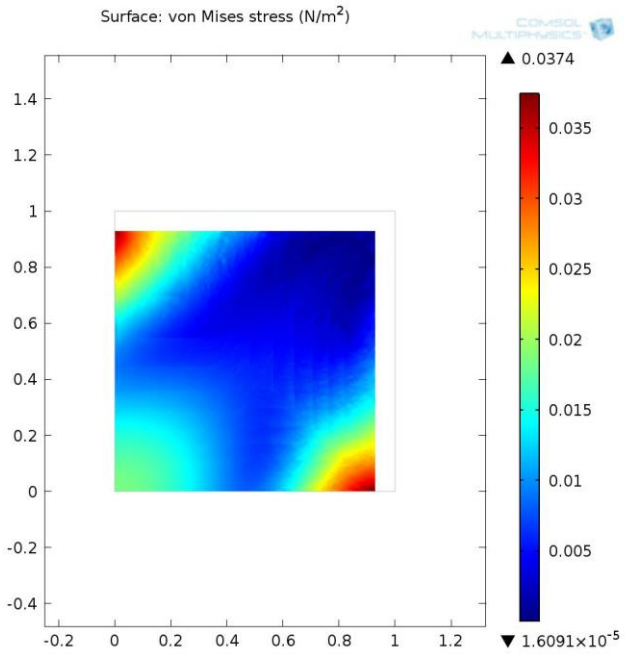


Figure 8.14: von Mises stress plot showing the stresses in (Pa) due to the -275.64°C temperature applied for ν = 0.49

8.13 Determination of Temperatures to simulate 50% shrinkage

Exactly the same process as that for the 35% shrinkage was repeated for a 50% shrinkage, where the properties are different, as denoted in Table 8.2.

8.14 Herculite Model Properties and Results

The properties used for the Herculite model are given in Table 8.9.

Table 8.9: Material properties and thermal load for the square plate Herculite Model

Young's Modulus (E)	4.18 GPa
Poisson's' ratio (ν)	0.24
Coefficient of Thermal Expansion (α)	32.6±1.6 x10^{-6} °/K
Density (ρ)	0 kg/m^3
T_{Ref}	0 °K

The results for this numerical experiment are given in Table 8.10 and Figure 8.15. It was noted that the amount of shrinkage was not affected by the change in the Young's modulus. The generated stress was shown to be affected as shown in Figure 8.17.

Table 8.10: Results of temperature shrinkage (50%) numerical experiment for Herculite

T (°C)	(ΔL/L)	(ΔL/L) %	T (°C)	(ΔL/L)	(ΔL/L) %
0	0.0000	0	-110	-0.0035	-0.36
-10	-0.0003	-0.03	-120	-0.0039	-0.39
-20	-0.0007	-0.07	-130	-0.0042	-0.42
-30	-0.0009	-0.09	-140	-0.0046	-0.46
-40	-0.0013	-0.13	-150	-0.0049	-0.49
-50	-0.0016	-0.16	-160	-0.0052	-0.52
-60	-0.0019	-0.19	-170	-0.0055	-0.55
-70	-0.0023	-0.23	-180	-0.0059	-0.59
-80	-0.0026	-0.26	-190	-0.0062	-0.62
-90	-0.0029	-0.29	-200	-0.0065	-0.65
-100	-0.0032	-0.33			

The line of best fit for this data was exactly the same as that for the 35% shrinkage and is also represented by Eq. (8.1).

$$\left(\frac{\Delta L}{L}\right)\% = 0.00326T \qquad (8.1)$$

Using equation (8.1) and the required shrinkage value for Herculite from Table 8.2, $\left(\frac{\Delta L}{L}\right)\% = 0.459204$, this equation can then be rearranged to determine the actual value of the temperature to be applied in order to produce this displacement.

$$-0.459204 = 0.00326T$$
$$\therefore T = \frac{-0.459204}{0.00326} = -140.86\,°C \tag{8.1}$$

The model was re-run with this temperature change, producing the result given in Figures 8.16 and 8.17. As can be seen from Figure 8.17, the von Mises stress generated in this unconstrained square element is negligible enough to be equivalent to a zero stress field.

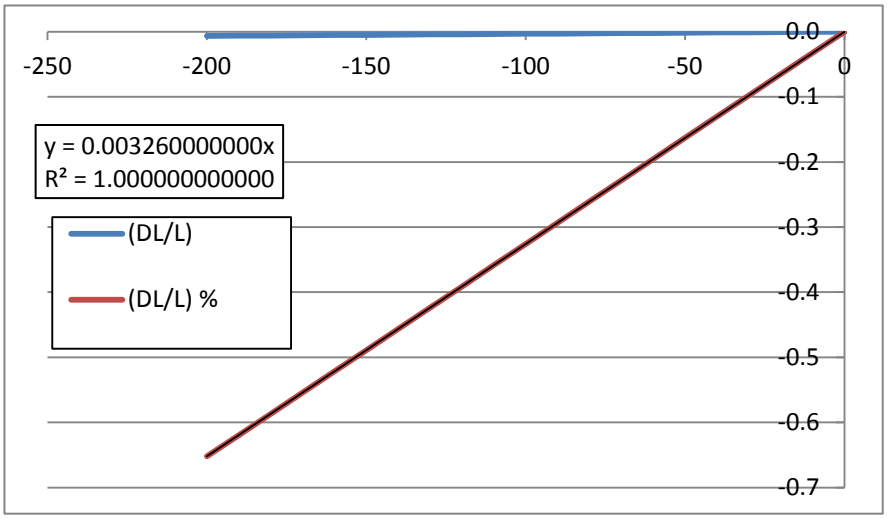


Figure 8.15: Plot of the data from Table 5 to determine line of best fit

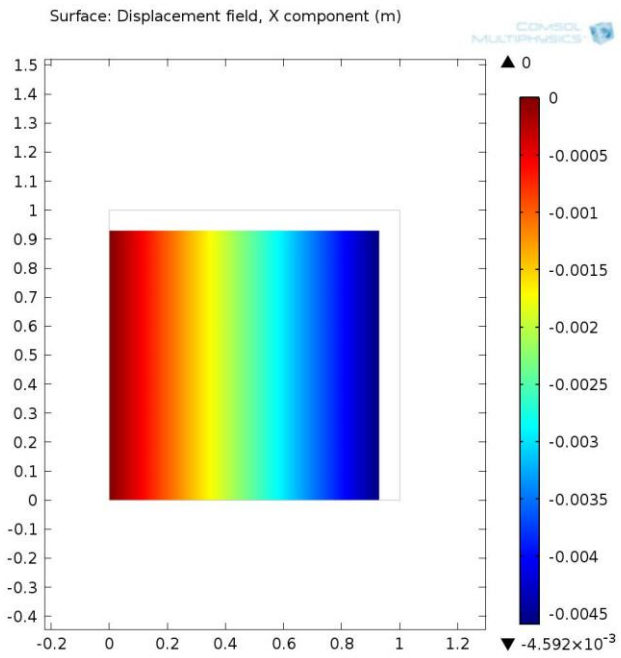


Figure 8.16: Displacement plot showing the displacement due to the -140.86°C temperature applied

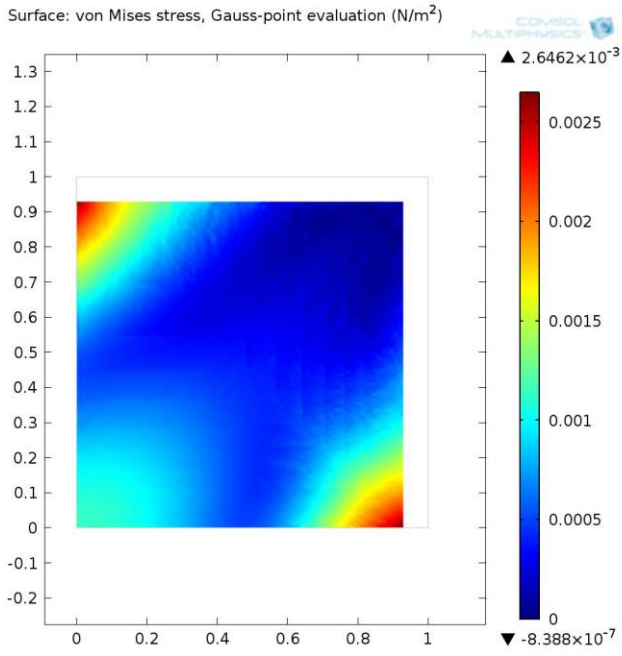


Figure 8.17: von Mises stress plot showing the stresses in (Pa) due to the -140.86°C temperature applied

8.15 Study on the different Poisson's ratio to maintain constant volume due to shrinkage process.

The Poisson's ratio was changed to the maximum value allowable by the programme COMSOL, before it break down. The value is given in Table 8.11. The results are given in Figures 8.18 and 8.19.

Table 8.11: Poisson's ratio for Herculite Model to model constant volume

Poisson's' ratio (ν)	0.49

As can be seen from Figures 8.18 and 8.19, there was no effect at all on the temperature which was necessary to provide the required shrinkage, however there is a considerable increase in the von Mises stress. However although the maximum stress experienced is 0.0521 Pa, this value is still negligible small.

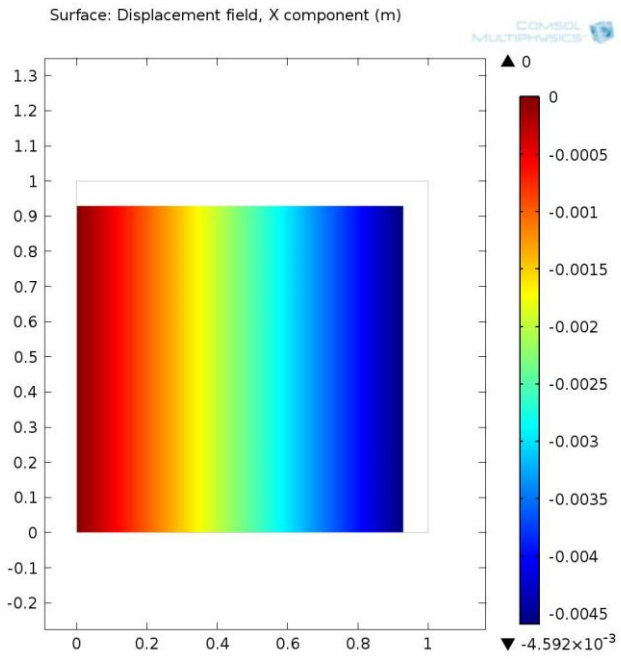


Figure 8.18: Displacement plot showing the displacement due to the -140.86°C temperature applied for ν = 0.49

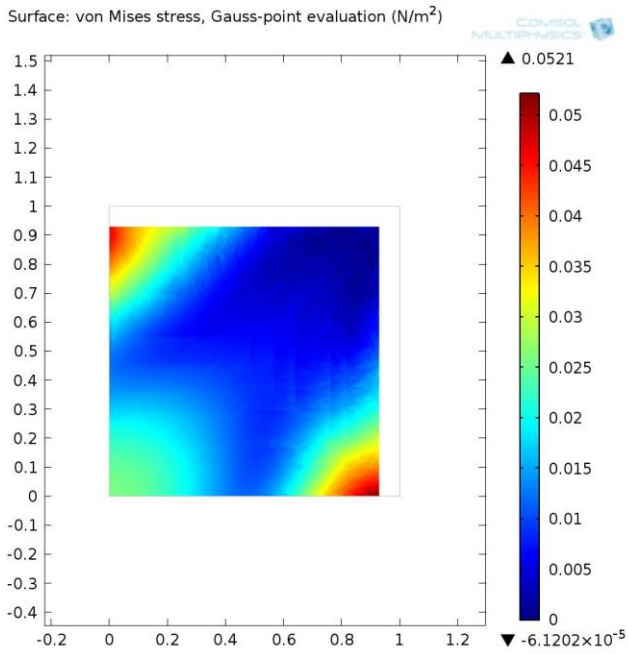


Figure 8.19: von Mises stress plot showing the stresses in (Pa) due to the -140.86°C temperature applied for $\nu = 0.49$

8.16 Fuji Model Properties and Results

The properties used for the Fuji model are given in Table 8.12.

Table 8.12: Material properties and thermal load for the square plate Fuji Model

Young's Modulus (E)	8.8 GPa
Poisson's' ratio (ν)	0.3
Coefficient of Thermal Expansion (α)	10.8 x10^{-6} °/K
Density (ρ)	0 kg/m^3
T_{Ref}	0 °K

As was the case for Herculite with the 50% shrinkage rate, for Fuji the Young's modulus variation did not affect the actual shrinkage value. It has however, affected the stress level. This means that Equation (8.2) can be used to determine the temperature to provide the 50% shrinkage for the Fuji.

$$\left(\frac{\Delta L}{L}\right)\% = 0.001081205T \tag{8.2}$$

Using equation (8.2) and the required shrinkage value for Fuji from Table 8.2, $\left(\frac{\Delta L}{L}\right)\% = 0.425273$, this equation was rearranged to determine the actual value of the temperature to be applied in order to produce this displacement.

$$-0.425273 = 0.001081205T$$
$$\therefore T = \frac{-0.425273}{0.001081205} = -393.33°C$$

The model was re-run with this temperature change; however the linear shrinkage value obtained was -0.004248, which is -0.4248%. This value is 0.111347% too small, so the temperature value should be increased by a factor of 1.00111347, meaning that the temperature should be: T = -393.7704°C. Working shown in equation (8.3)

$$T_{Fraction} = \frac{-0.425273}{-0.4248} = 1.001113465$$
$$\therefore T_{New} = 1.001113465 \times -393.3324 = -393.77\ °C \tag{8.3}$$

This new slightly increased temperature gave the correct required shrinkage. The results of the analysis are given in Figures 8.20 and 8.21.

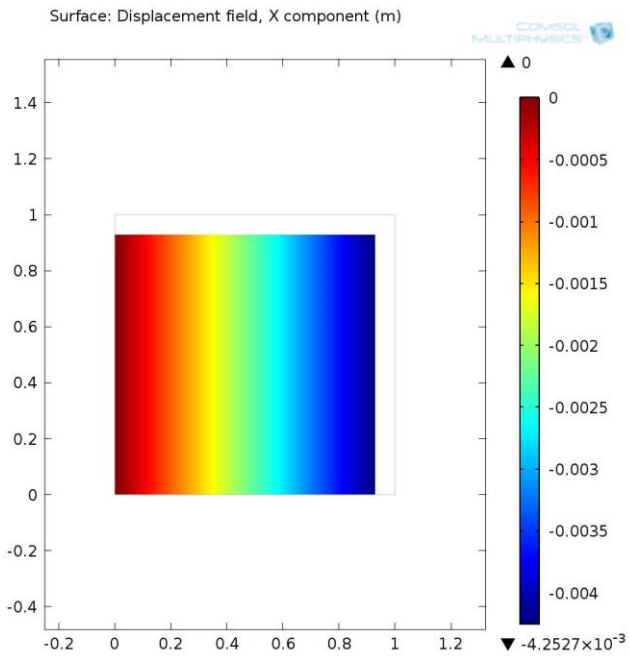


Figure 8.20: Displacement plot showing the displacement due to the -393.77°C temperature applied

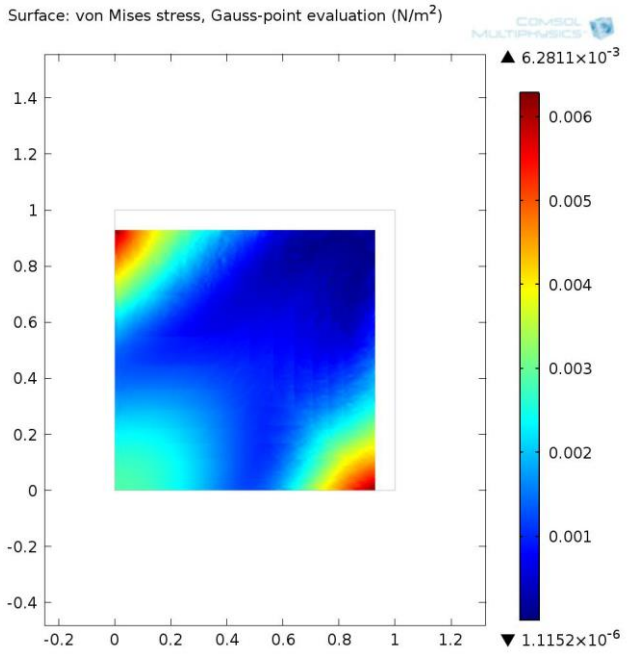


Figure 8.21: von Mises stress plot showing the stresses in (Pa) due to the -393.77°C temperature applied

As can be seen from Figure 8.21, the von Mises stress generated in this unconstrained square element was very small to be equivalent to a zero stress field.

8.17 Study on the different Poisson's ratio to maintain constant volume due to shrinkage process.

The Poisson's ratio was changed to the maximum value allowable by the programme COMSOL, before it break down. The value is given in Table 8.13. The results are given in Figures 8.22 and 8.23.

Table 8.13: Poisson's ratio for Fuji Model to model constant volume

Poisson's' ratio (ν)	0.49

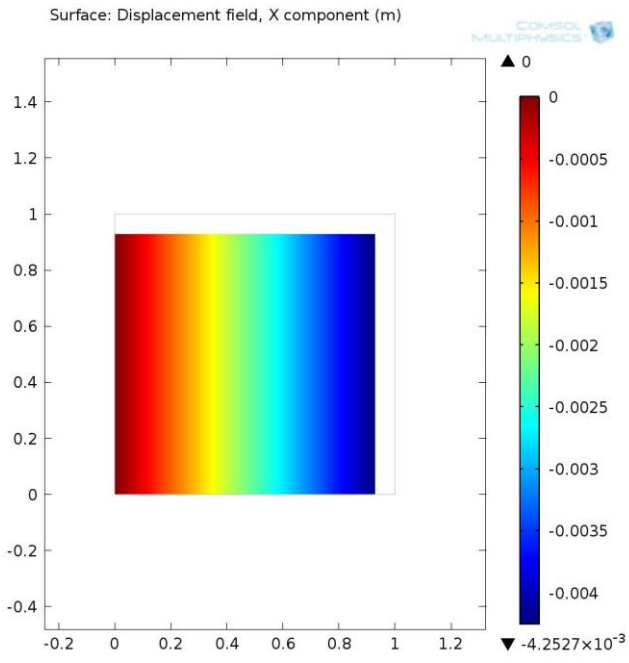


Figure 8.22: Displacement plot showing the displacement due to the -393.77°C temperature applied for ν = 0.49

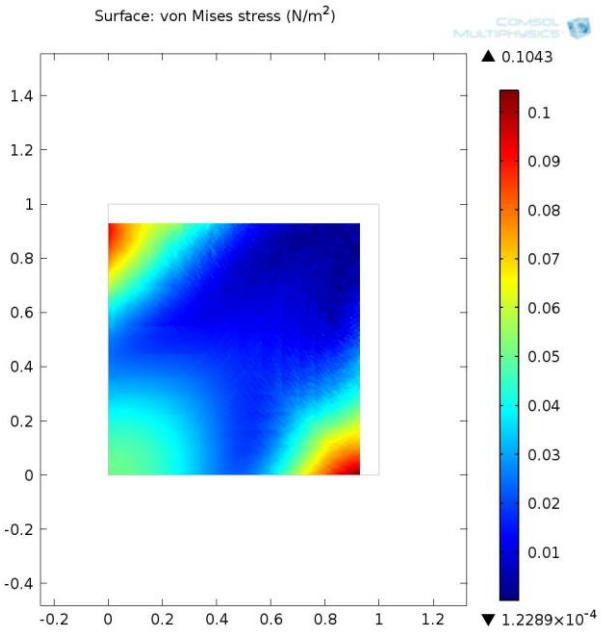


Figure 8.23: von Mises stress plot showing the stresses in (Pa) due to the -393.77°C temperature applied for $\nu = 0.49$

As can be seen from Figures 8.22 and 8.23, there was no effect at all on the temperature which was required to provide the required shrinkage. There was however, a considerable increase in the von Mises stress. The maximum stress experienced was 0.1043 Pa, this value was negligible small.

8.18 Summary of Temperatures and Properties for the 35% and 50% Shrinkage Models

All necessary property values for the 35% and 50% shrinkage models were listed in Table 8.14.

Table 8.14: Temperature required to provide the 35% and 50% shrinkage in Herculite and Fuji materials

	Material	35% shrinkage		50% shrinkage	
		E (GPa)	ΔT (°C)	E (GPa)	ΔT (°C)
	Resin composite Herculite XRV [1,9, 10]	2.185	-98.60°C	4.18	-140.86°C
	Glass Ionomer Cement, Fuji II LC [6]	4.6	-275.64°C	8.8	-393.77°C

8.19 Evaluation of stress distribution in Preliminary Restoration Model

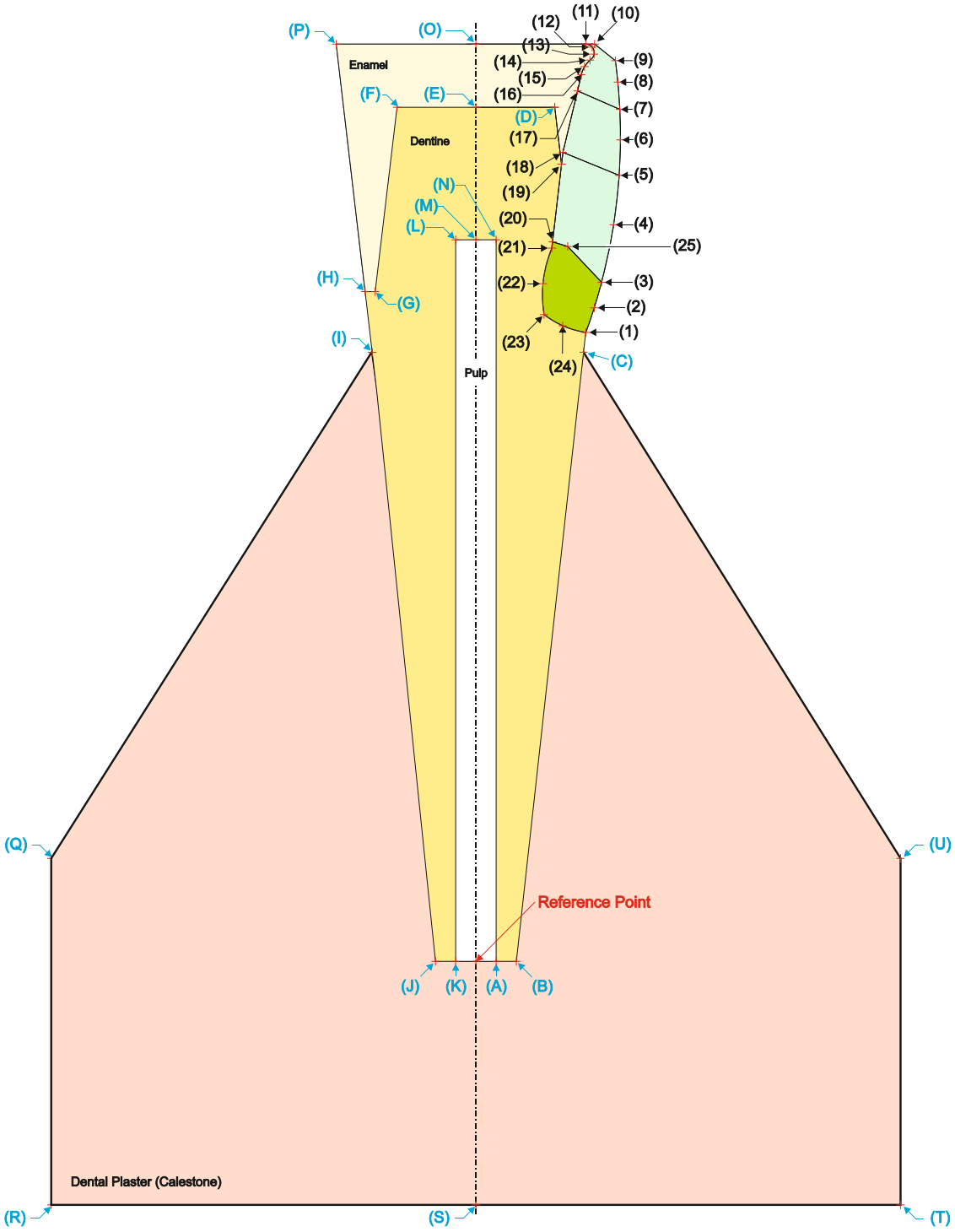


Figure 7.6 : Preliminary restoration model

Figure 7.6 represent the 2D model which was constructed and explained in chapter 7. All the coordinates as calculated were in mm as can be seen from Table 7.1. Once they are imported into the FE programme (COMSOL) they were all converted to metres for consistency with the material properties. The model was represented in Plane Stress.

8.20 Addition of restorations sections in the preliminary model

All models can be analysed using one FE model by using COMSOL software. The idea was to build one FE model (with all the restorations layers) which then has each layer deactivated until all the Herculite layers were applied and its stresses calculated.

The numbers of the layers that were activated at different times are given in Figure 8.24.

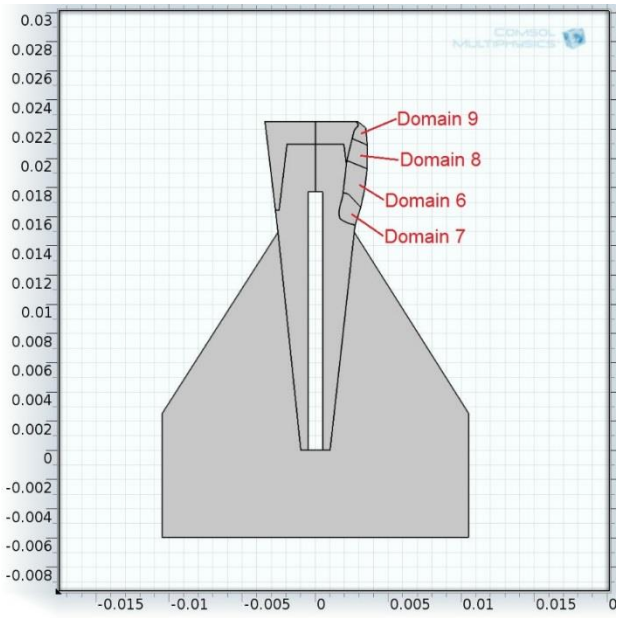


Figure 8.24: Stylised tooth with the different layers to be activated, starting with layer 7, then 6, 8 and finally 9

To begin with, for Step 1, domains 6, 8 and 9 are deactivated, leaving only domain 7, in which the thermal load by means of a temperature of -275.64°C was applied to the Fuji material to represent the shrinkage.

The three stresses analysed are the two local principal stresses (11 and 22) and the shear stress (12). These are plotted in Figures 8.25, 8.26 and 8.27 respectively.

8.20.1 Step 1: Addition of the Fuji II layer

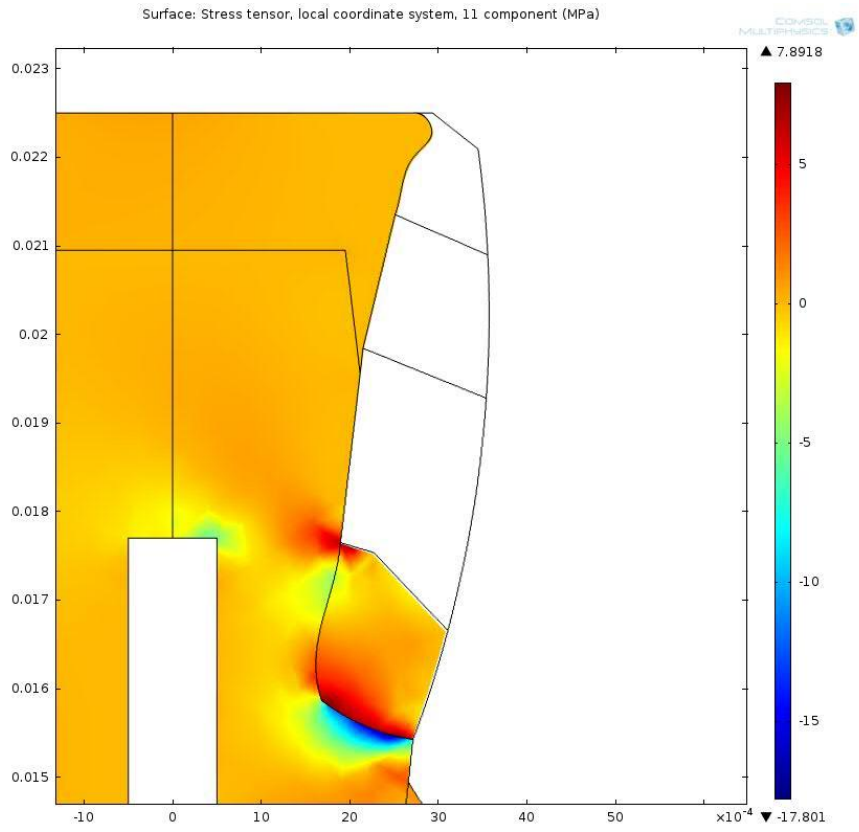


Figure 8.25: Principal stress (11), which shows the direct stresses in the structure due to the addition of the Fuji II layer

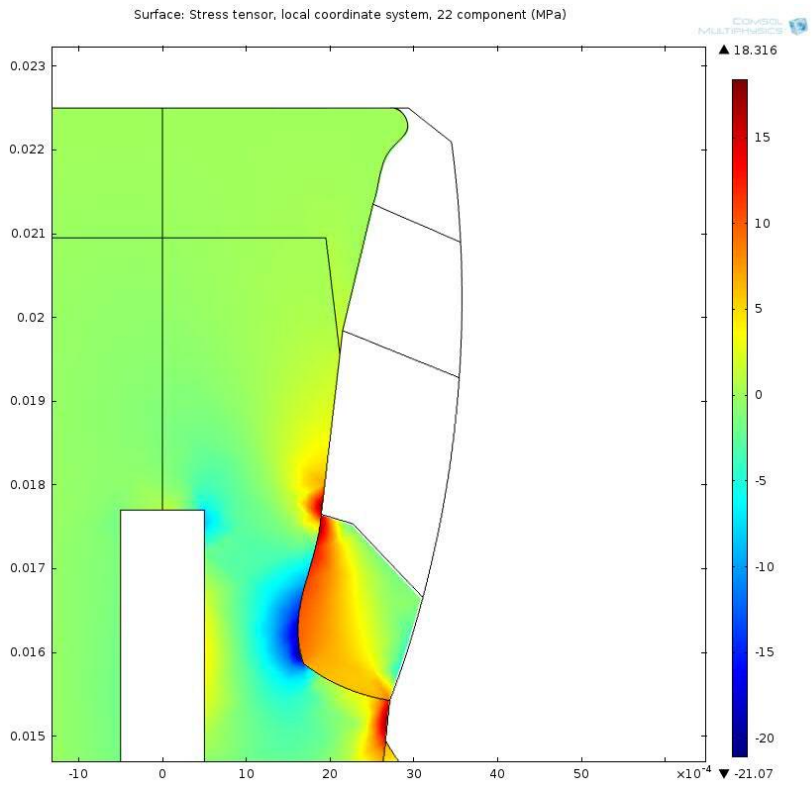


Figure 8.26: Principal stress (22), which shows the direct stresses in the structure due to the addition of the Fuji II layer

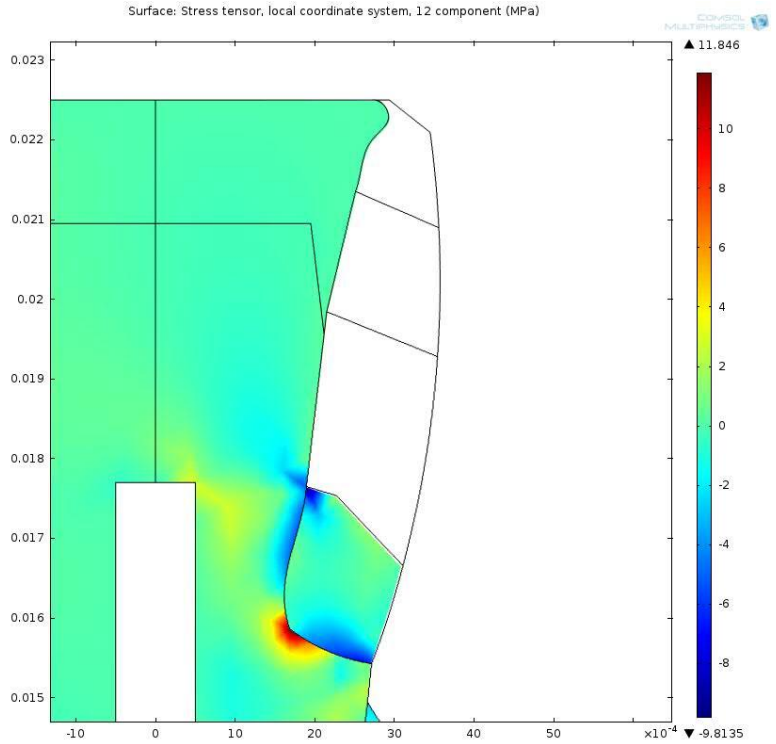


Figure 8.27: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the Fuji II layer

As can be seen in all previous figures 8.25; 8.26, 8.27, the stresses are within the bounds of the limits tensile, compressive and shear stresses for the dentine, enamel, adhesive and Fuji II materials. Therefore, there are no indications from the curing process that high stresses are generated from the application of the Fuji II material.

8.20.2 Step 2: Addition of the 1st Herculite restoration layer.

Domain 6 was added to the model. The thermal load on the Resin composite Herculite XRV was of -98.60C to represent its shrinkage. The corresponding results for the two principal stresses (11 and 22) and the shear stress (12) were plotted in Figures 8.28, 8.29 and 8.30 respectively.

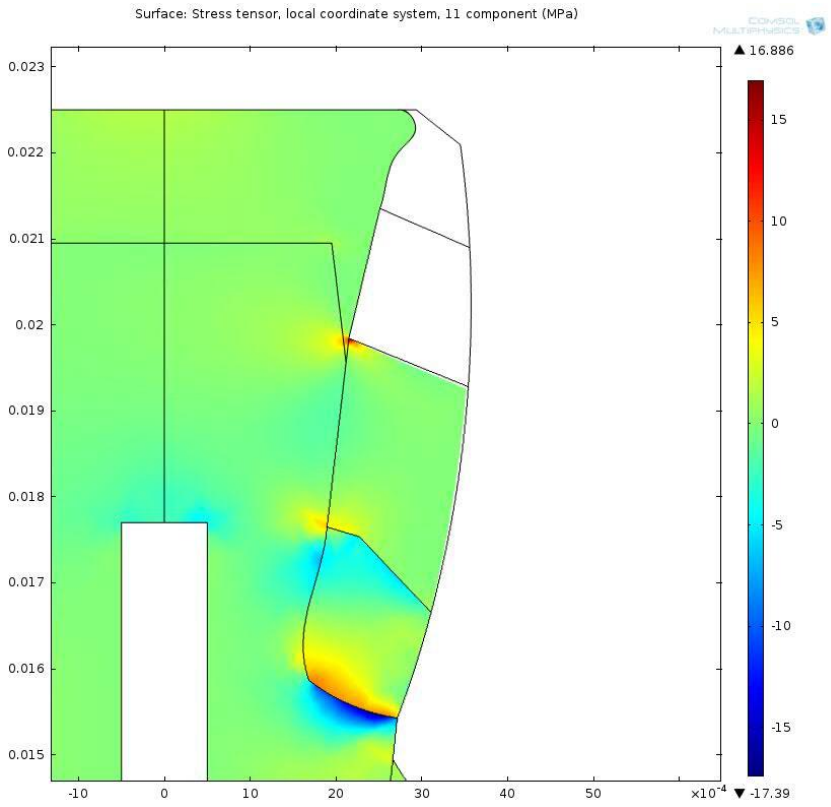


Figure 8.28: Principal stress (11), which shows the direct stresses in the structure due to the addition of the 1st Herculite layer

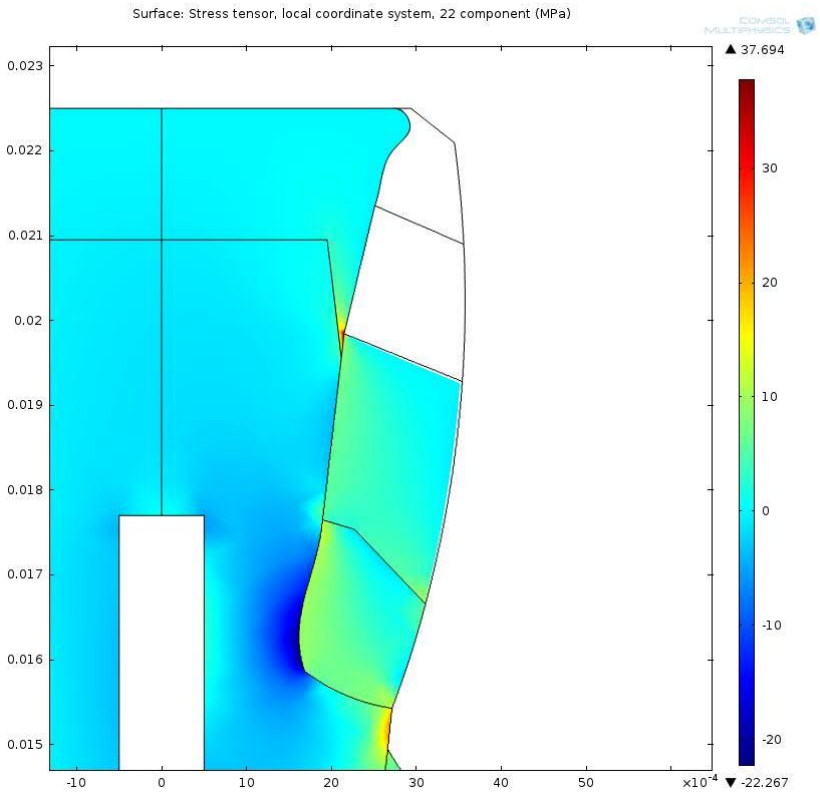


Figure 8.29: Principal stress (22), which shows the direct stresses in the structure due to the addition of the 1st Herculite layer

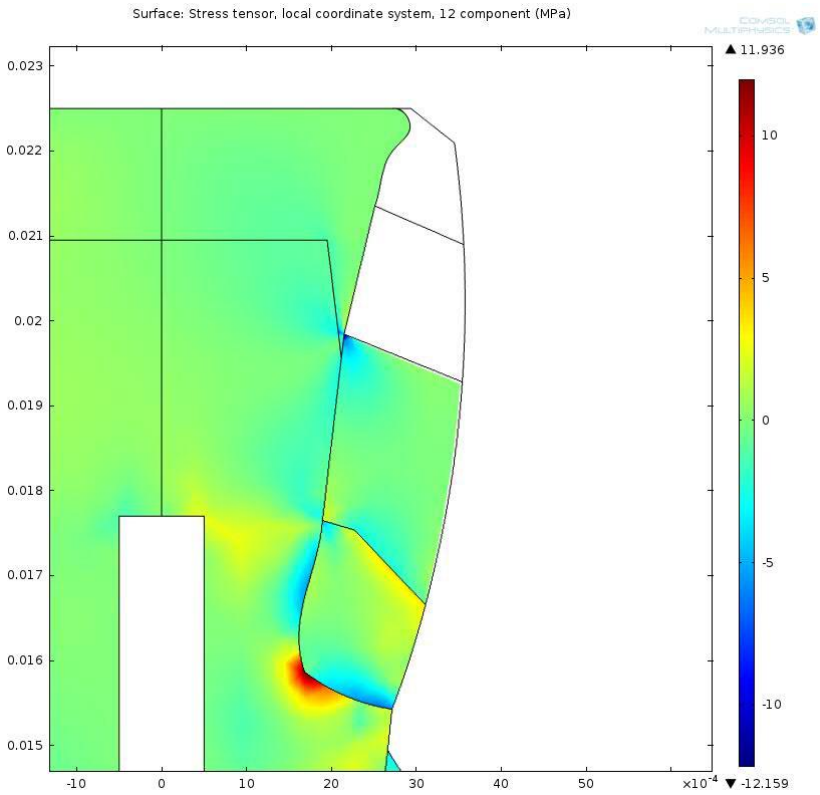


Figure 8.30: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the 1st Herculite layer

As can be seen in all previous figures 8.28; 8.29, 8.30, the stresses are within the bounds of the limits of tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II and Herculite materials.

8.20.3 Step 3: Addition of the 2nd Herculite restoration layer.

Domain 8 was added to the model. The thermal load on the Resin composite Herculite XRV was of -98.60°C to represent its shrinkage. The corresponding results for the two principal stresses (11 and 22) and the shear stress (12) are plotted in Figures 8.31, 8.32 and 8.33 respectively.

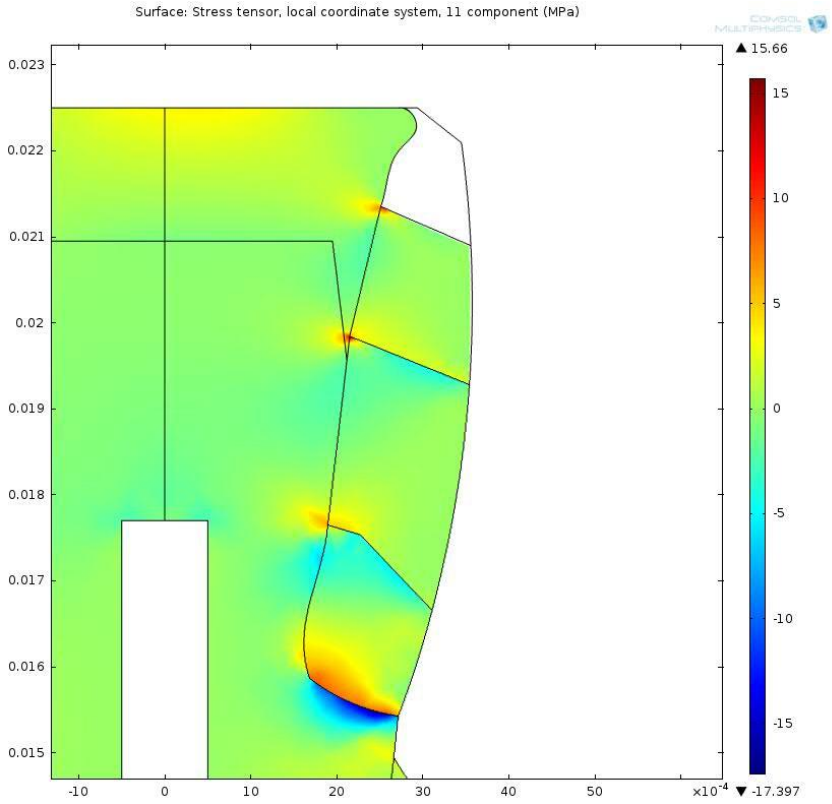


Figure 8.31: Principal stress (11), which shows the direct stresses in the structure due to the addition of the 2nd layer of the Herculite

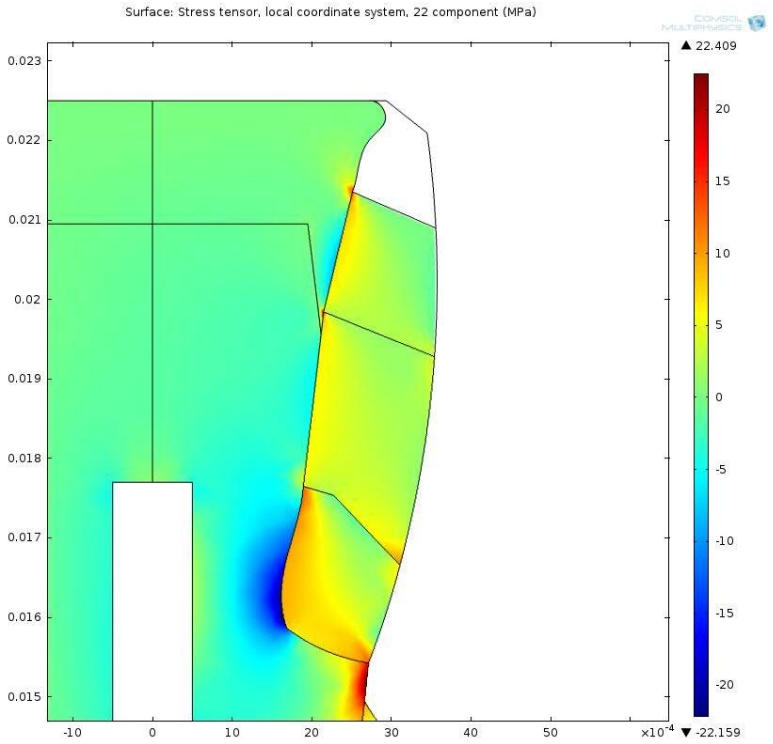


Figure 8.32: Principal stress (22), which shows the direct stresses in the structure due to the addition of the 2nd layer of the Herculite

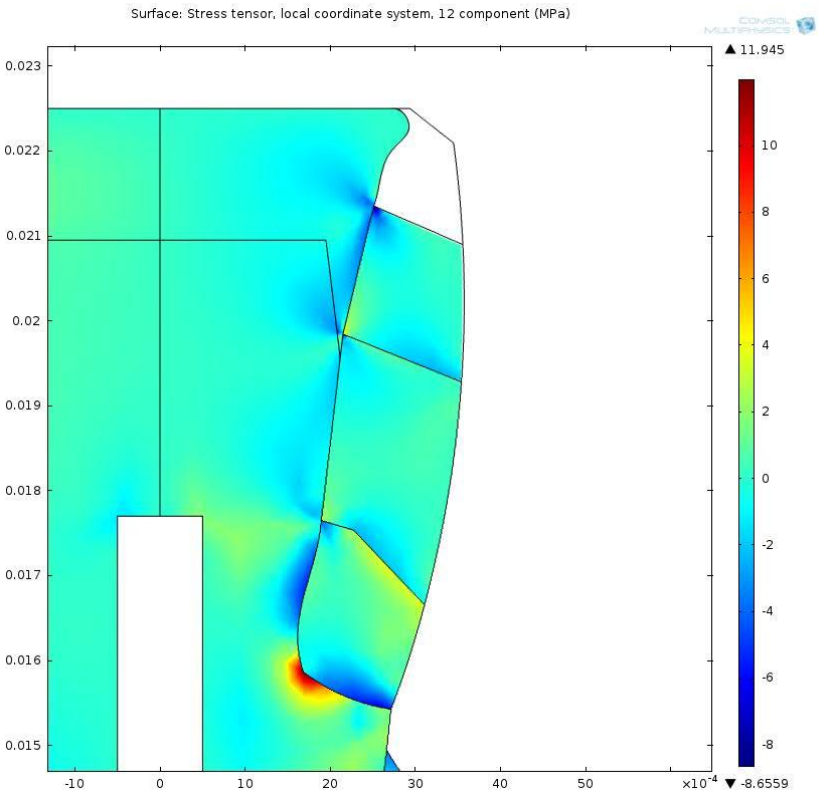


Figure 8.33: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the Fuji layer

As can be seen in all previous figures 8.31; 8.32, 8.33., the stresses are within the bounds of the limits of tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II and Herculite materials. One other thing which can be seen was that the addition of a new layer can reduce the magnitude of the stresses induced by the curing of a previous layer.

8.20.4 Step 4: Addition of the 3rd Herculite restoration layer.

Domain 9 was added to the model. The thermal load on the Resin composite Herculite XRV was of -98.60209°C to represent its shrinkage. The corresponding results for the two principal stresses (11 and 22) and the shear stress (12) are plotted in Figures 8.34, 8.35 and 8.36 respectively.

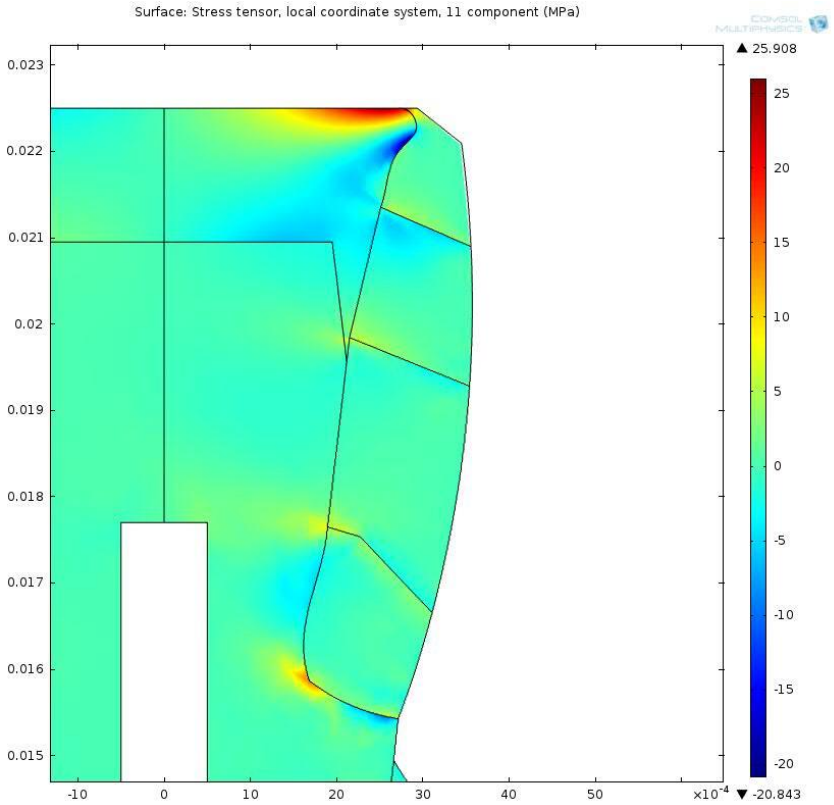


Figure 8.34: Principal stress (11), which shows the direct stresses in the structure due to the addition of the third layer of the Herculite

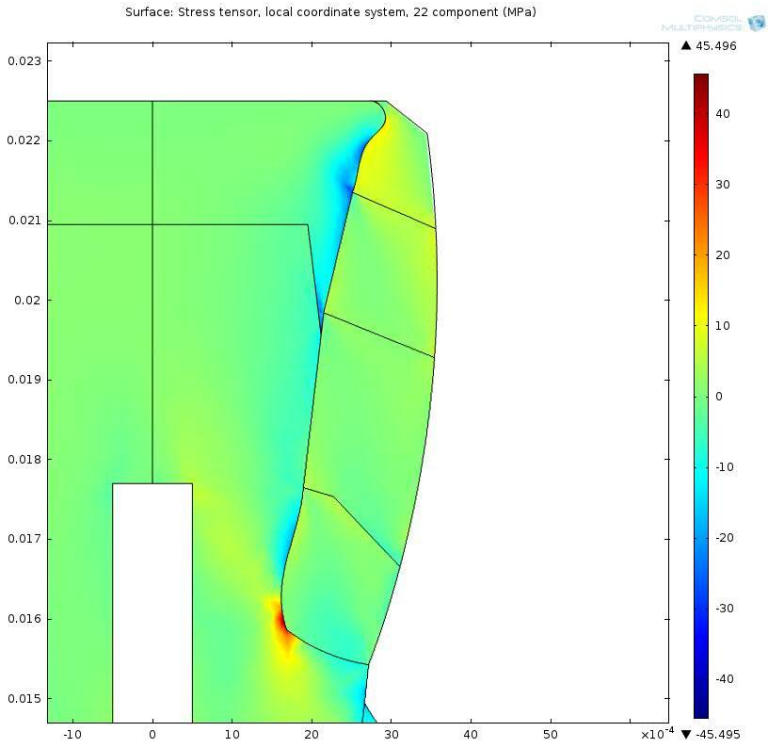


Figure 8.35: Principal stress (22), which shows the direct stresses in the structure due to the addition of the third layer of the Herculite

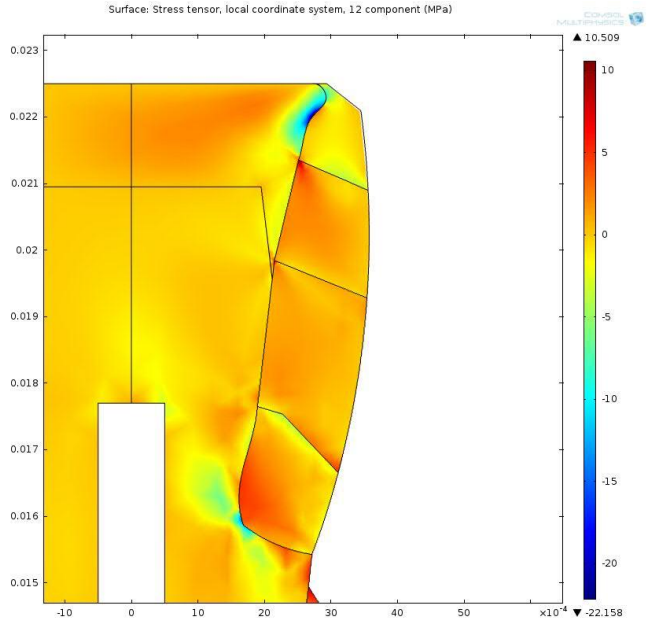


Figure 8.36: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the 3rd layer of Herculite

As can be seen in all previous figures 8.34; 8.35, 8.36, the stresses are within the bounds of the limits tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II and Herculite materials. One other thing which can be seen was that the addition of a new layer can relieve (reduce) the magnitude of the stresses induced by the curing of a previous layer.

8.21 Preliminary results:

For this model, the analysis consisted of applying only the 35% shrinkage to the Fuji and then Herculite. The reason for this was that in preliminary analysis to test the model it was found that the 35% shrinkage model gave a reasonable representation of the stress distribution. But more importantly it was found that the entire Fuji and Herculite material realistically behave in a viscoelastic manner, so using a liner elastic model can at best show how the stresses are distributed once the material hardens and becomes linear-elastic. However, as there is no published data on both the viscoelastic nature of these two materials before curing and after curing, this analysis is then qualitative, in that it could show the regions where stresses are induced from the shrinkage process at each stage of the restoration.

8.22 Evaluation of the stress distribution in the complete/anatomical tooth Model

In the previous section the preliminary model was explored. In this section a more complete/anatomical model was considered.

Stress analysis using the complete/anatomical model of the maxillary second premolar (Figure 7.10) which was developed as mentioned in Chapter 7 to investigate the stress distribution in sandwich restoration.

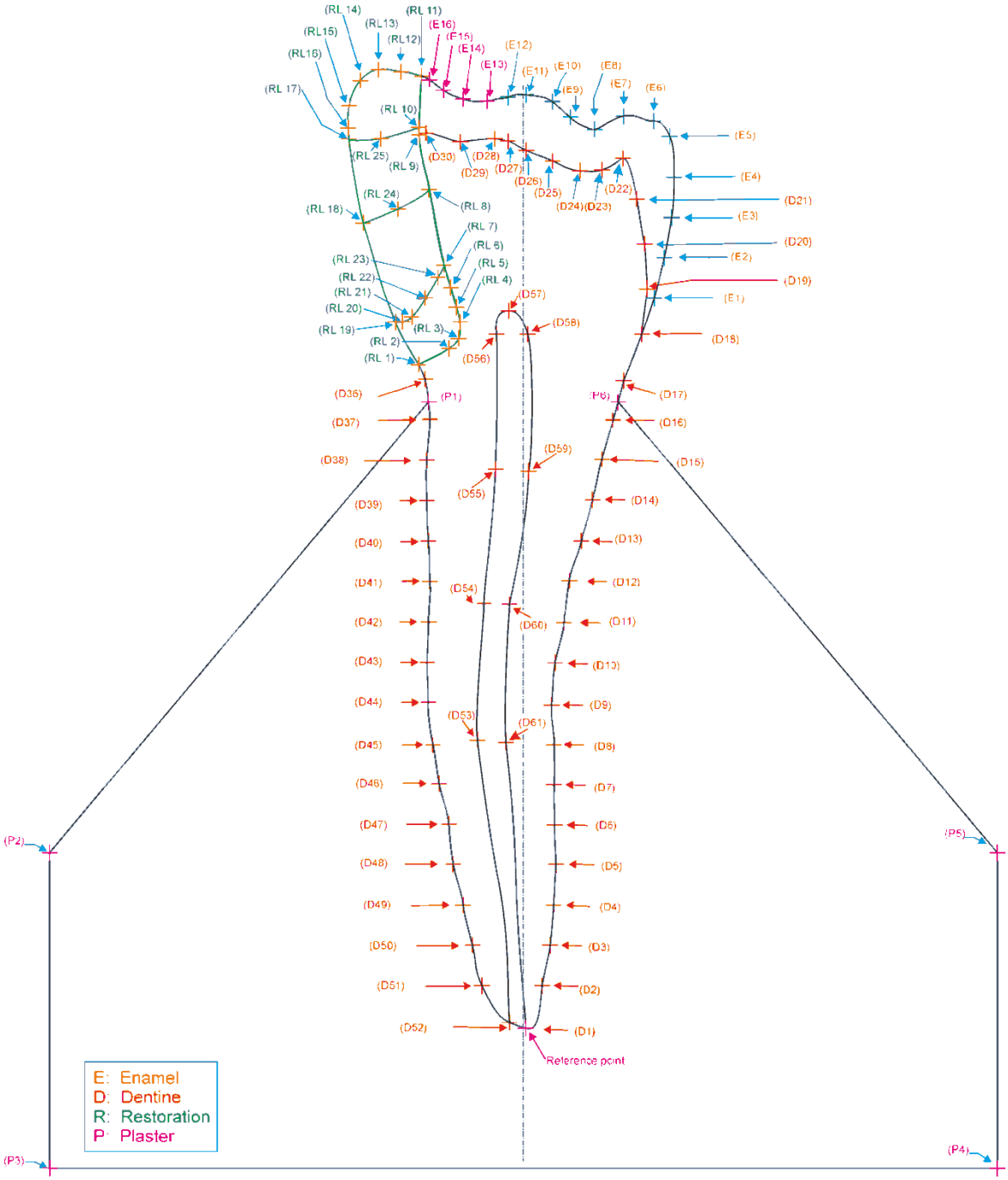


Figure 7.10: Complete/anatomical model of the Maxillary 2nd premolar tooth with only one restoration section

8.22.1 Step 1: Addition of Fuji II layer.

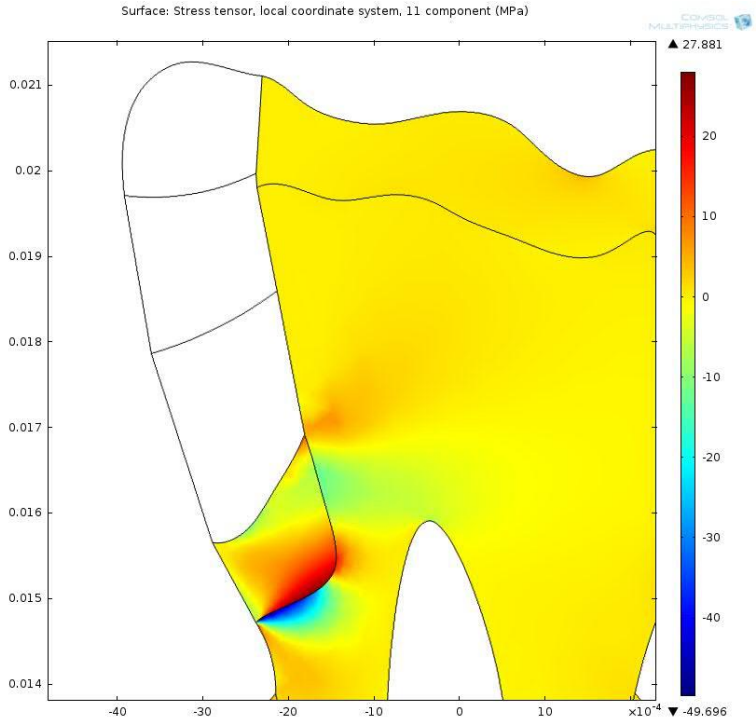


Figure 8.37: Principal stress (11), which shows the direct stresses in the structure due to the addition of the Fuji II layer

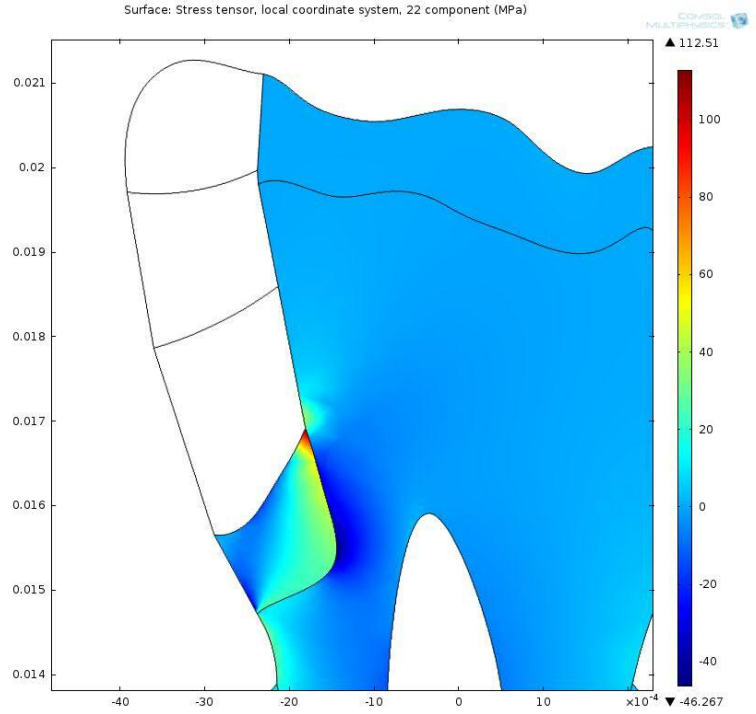


Figure 8.38: Principal stress (22), which shows the direct stresses in the structure due to the addition of the Fuji II layer

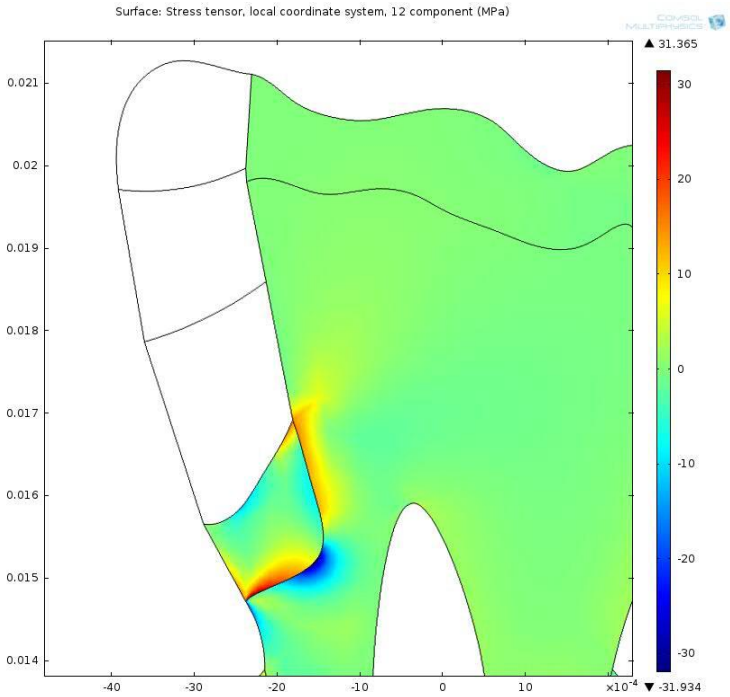


Figure 8.39: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the Fuji layer

8.22.2 Step 2: Addition of the 1st Herculite layer.

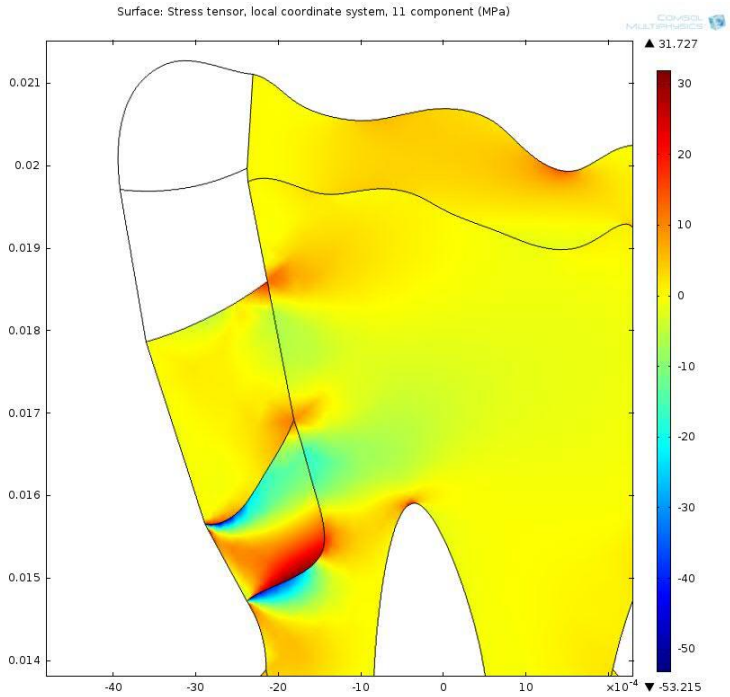


Figure 8.40: Principal stress (11), which shows the direct stresses in the structure due to the addition of the 1st Herculite layer

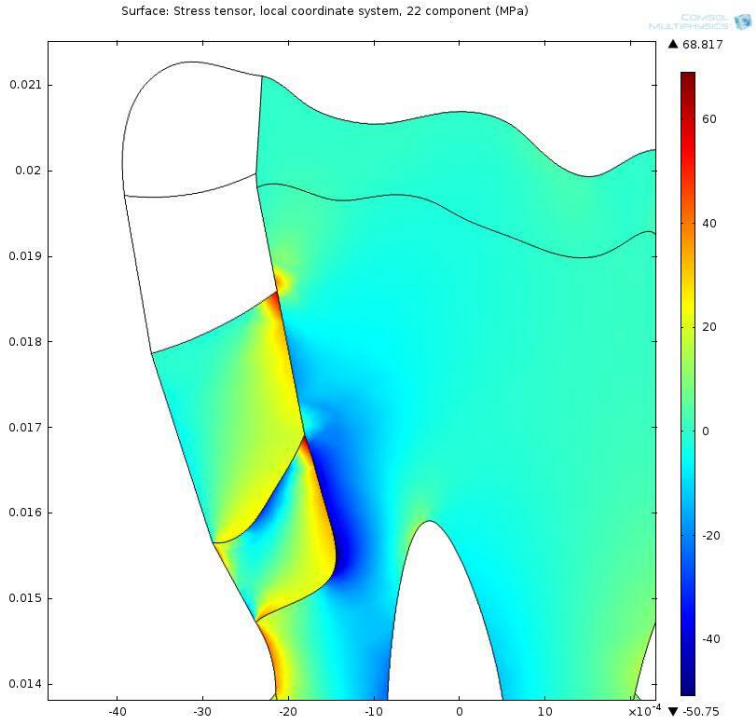


Figure 8.41: Principal stress (22), which shows the direct stresses in the structure due to the addition of the 1st Herculite layer

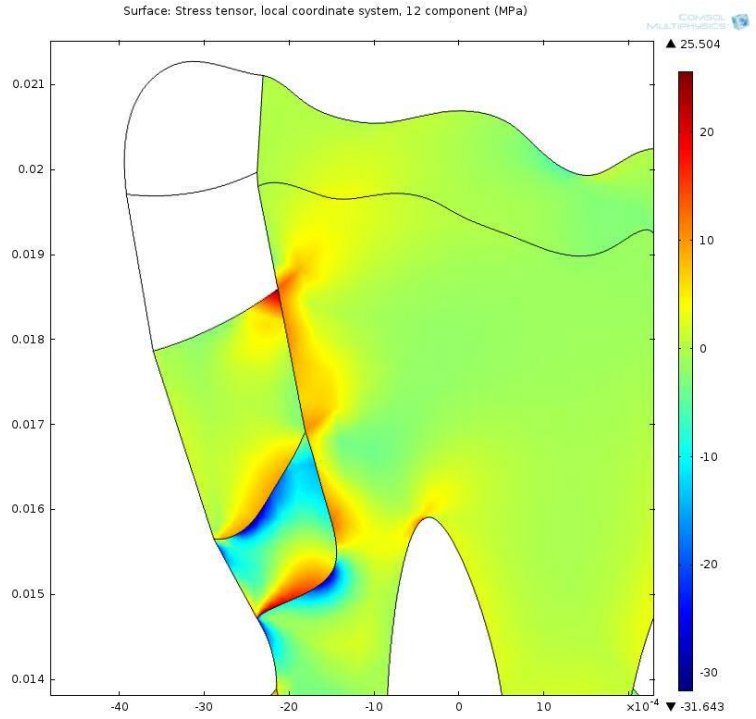


Figure 8.42: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the 1st Herculite layer

8.22.3 Step 3: Addition of the 2nd Herculite layer.

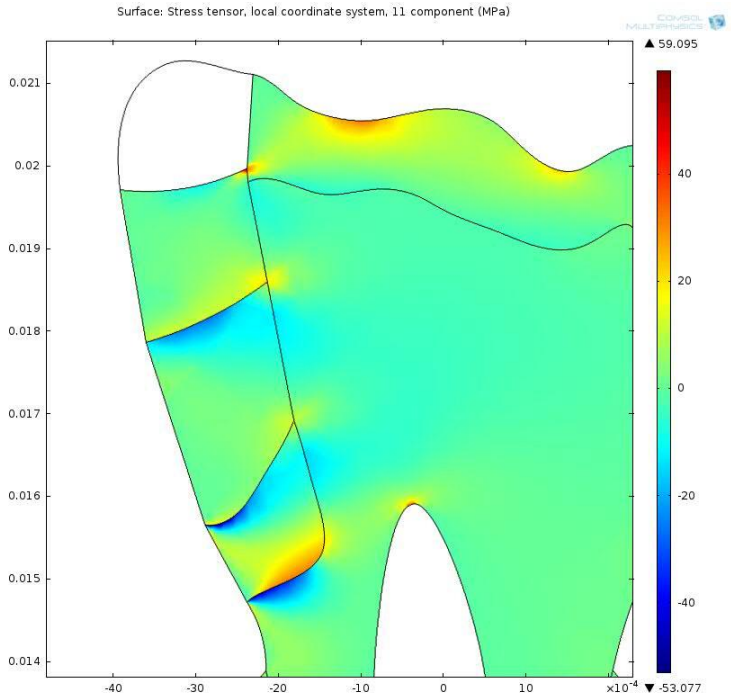


Figure 8.43: Principal stress (11), which shows the direct stresses in the structure due to the addition of the 2nd Herculite layer

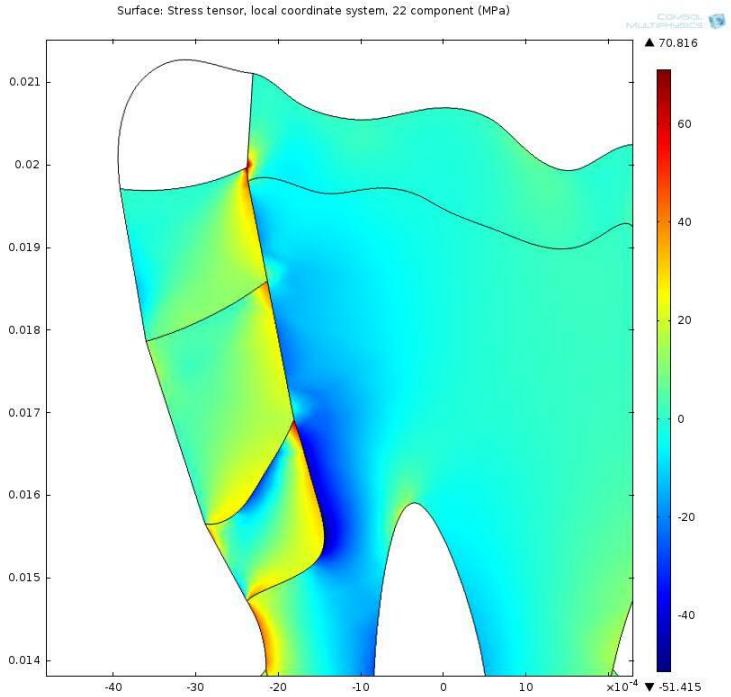


Figure 8.44: Principal stress (22), which shows the direct stresses in the structure due to the addition of the 2nd Herculite layer

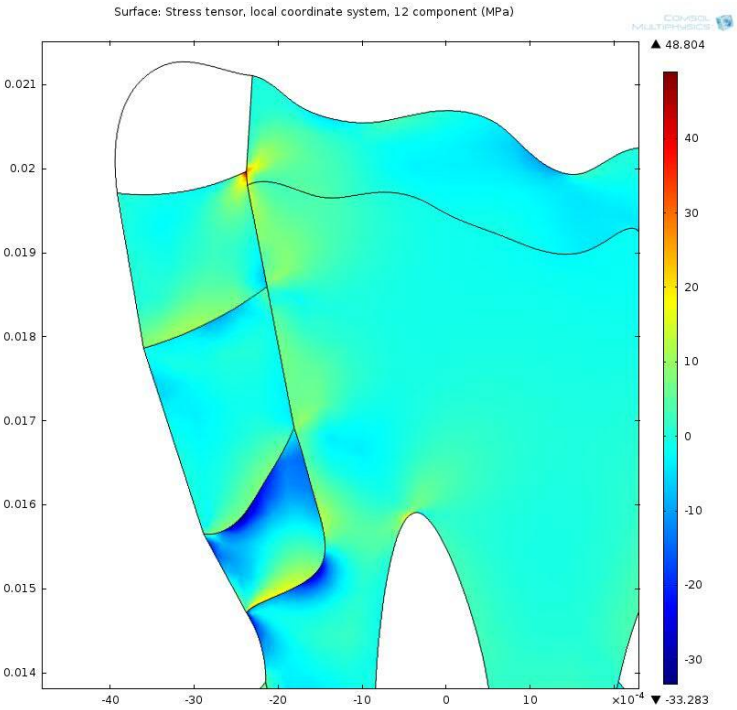


Figure 8.45: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the 2nd Herculite layer

8.22.4 Step 4: Addition of the 3rd Herculite layer.

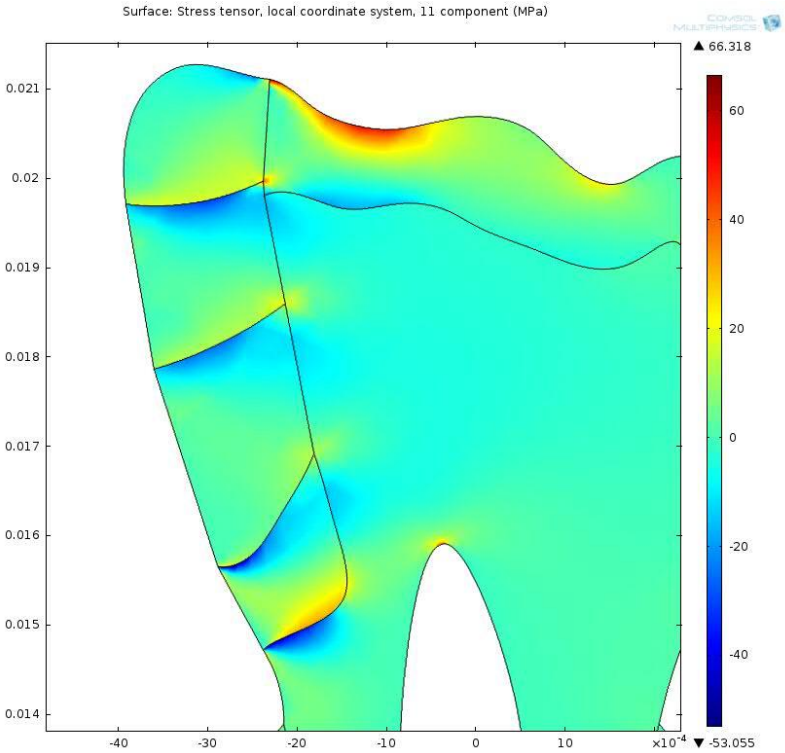


Figure 8.46: Principal stress (11), which shows the direct stresses in the structure due to the addition of the 3rd Herculite layer

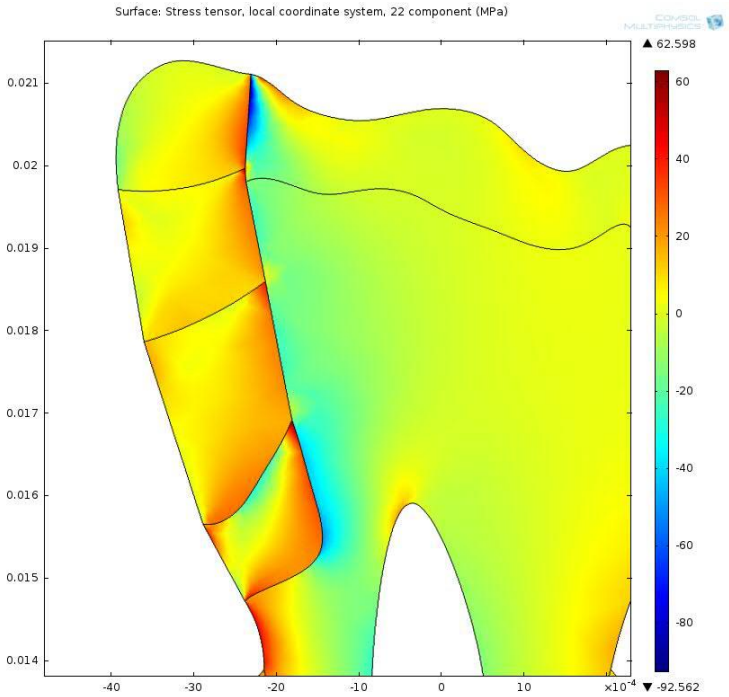


Figure 8.47: Principal stress (22), which shows the direct stresses in the structure due to the addition of the3rd Herculite layer

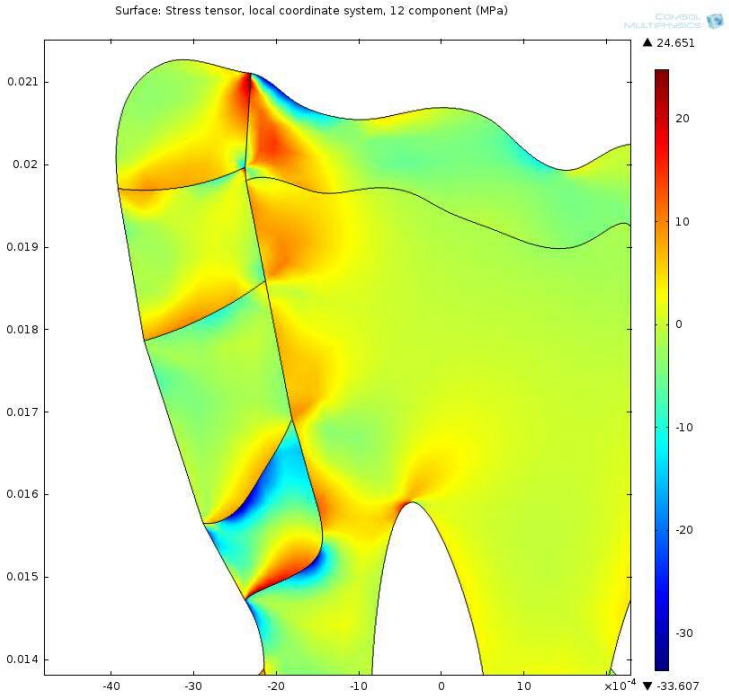


Figure 8.48: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the 3rd Herculite layer

It is clear from all of the results presented from Figures 8.37 to Figure 8.48, that the shape of the Fuji II layer and that of the Herculite has an effect on the stress level. Very steep sharp edges between the Fuji II and the dentine seem to suggest regions of high stresses on both the Fuji and dentine. The stresses are however, within the bounds of the limits of the tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II and Herculite materials.

8.23 Discussions

The result of Preliminary and the idealised FEA models showed clearly that the stresses generated, when the Fuji II material was cured separately in the proximal RMGIC/RC sandwich restoration, were within the limits of the tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II, and Herculite materials. As the stress level is not exceeding the limit, the proposed co-curing protocol by Knight (2006) did not appear to provide any further benefit in this regards. Previous work by (van Dijken et al., 1999) has reported that modified open-sandwich restoration using resin modified glass ionomer can be considered as an alternative to amalgam restorations. They have however, postulated a failure rate of about 19% after 6 years follow up. The failure was linked to tooth fracture, and secondary caries following dissolution of the RMGIC. They have also found that the use of polyacrylic acid to condition the cavity has been shown to contribute to the higher failure rate. This finding has led other researcher to start using the adhesive system before the application of the RMGIC which has shown to increase its bond strength with the tooth structure (Khoroushi et al., 2012a). This approach was supported in part with

the presence of resin components in both the adhesive and resin modified glass ionomer which allows for covalent bond formation between the two materials. This method was also recommended by many previous research (Besnault et al., 2004; Geerts et al., 2010; Dursun and Attal, 2011; Poggio et al., 2014).

From the stress distribution using the idealised model, areas of high stress were detected in areas of the restoration with sharp angulations and edges (Figures 8.37-8.48). This may have clinical implications, indicating that the restoration and the preparation outline should be kept as rounded as possible. However, it should be kept in mind that this analysis was only a linear elastic model. In order to obtain an accurate stress values, a viscoelastic model should be used.

The difficulty of comparing the results of this study to others derives from the fact that there is no previous research concerning investigation of the stress distribution of sandwich restoration using FEA.

The adhesive layer was initially omitted from this analysis as it was assumed to be very thin as per the manufacturer instruction of use (10 micron). This thickness could only have had negligible effect on the stresses and therefore there was no value in including it in the model.

8.24 Conclusion

Within the limitation of this FEA study, Sandwich restoration using Fuji II and Herculite using conventional curing protocol has generated stresses within the limits of tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji II and Herculite materials.

Chapter 9

Evaluating the effect of the adhesive layer thickness on the generated stress using the FEA

9.1 Introduction

Previous research has found that thick adhesive layer may have an adverse effect on the longavity of the restoration through debonding and crack propagation which leads to gap formation and induce microleakage. The shrinkage stress generated from the thick adhesive layer could negatively affect the bond strength of the adhesive material to the tooth structure (Hilton and Schwartz, 1995; de Menezes et al., 2013). **The aim of this part** of the study was to investigate the effect of the adhesive layer thickness on the generated stress using the FEA.

8.2 Calculation of Volumetric Shrinkage of the adhesive material used in the study

Since there was no data exists from the manufacturer and also from the previous research on the volumetric shrinkage for the adhesive layer, this part of the study required the use of the sections which was generted from the experimental work conducted in Chapter 6 (section 6.4) in which the adhesive was applied to the prepared cavity on the Typodont plastic teeth. The teeth section which showed a clear shrinkage of the adhesive was chosen in order to measure the area after shrinkage and compared with the area before shrinkage. All of the measurment were done by using CorelDraw software. Appendix D.,

shows the results on the area shrinkage and the corresponding volumetric shrinkage of the adhesive layer on the speciemens tested.

Table 9.1: Area shrinkage for specimens tested		
Specimen Name	**Area Ratios**	**Area Shrinkage**
13-90	0.917	0.083
16-105	0.963	0.037
19-135	0.956	0.044
17-120	0.919	0.081
	Average Area Shrinkage	0.061
	SD in Area Shrinkage	0.021
	% Area Shrinkage	**6.12**
	% Volumetric Shrinkage	**9.04**

Table 9.2: Relationship between linear, area and volumetric shrinkage for the 6.12% area shrinkage calculated from experiments

L	**∆L**	**∆L/L%**	**A**	**∆A**	**∆A/A %**	**V**	**∆V**	**∆V/V %**
1	0.031	3.109	1	0.061	6.121	1	0.090	9.04

This shows that the adhesive has a considerable volumetric shrinkage which was over 3 times greater than that for the Fuji or Herculite material. Such shrinkage could produce excessive stresses and hence lead to debonding of the tooth restoration, if the adhesive layer is excessively thick.

9.3 Determination of Temperatures to simulate 6.12% Area Shrinkage

The model of Figure 9.1 represents a quarter of a square plate of size 2 m which was used to determine the temperature required for the adhesive to shrink by 6.12% of its area. The 2D approximation used was Plain Stress, as it

disregards any 3D induced stresses which are present in the plain strain solution.

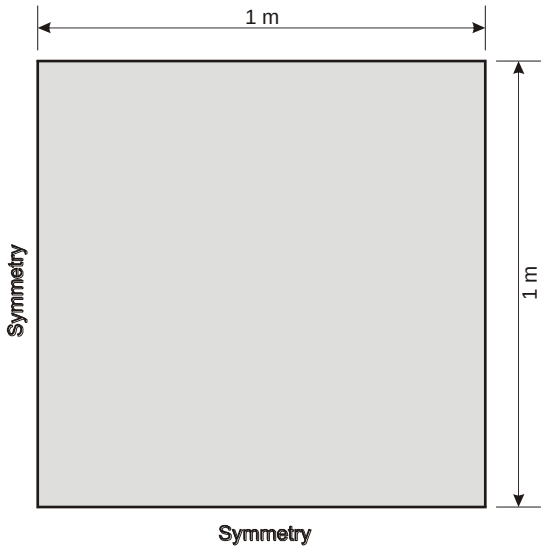


Figure 9.1: Quarter of plate design domain

The known properties for the Optibond Solo adhesive are given in Table 7.1, but are repeated below in Table 9.3. The value for its coefficient of thermal expansion is not known; however, in the current study as the researcher was trying to determine a nominal artificial temperature that combined with the coefficient of thermal expansion which would give the desired 6.12% area shrinkage, the nominal value of $10x10^{-6}$/°C was used.

Table 9.3: Properties for the Optibond Solo adhesive

	Elastic Modulus	Poisson's Ratio	Compressive Strength	Tensile Strength	Shear Strength	Thermal Expansion α	Volumetric shrinkage
	E (GPa)	ν	σ_C (MPa)	σ_T (MPa)	τ (MPa)	($/^oC$ $x10^{-6}$)	($\Delta V/V$) %
	1	0.3		25			9.04
Bonded with Enamel					34[15]		
Bonded with Dentine					31.3 ±2.7[18]		

The results for this numerical experiment are given in Table 9.4 and Figure 9.2.

Table 9.4: Results of temperature shrinkage to achieve 6.12% Area Shrinkage or 3.11% linear shrinkage

T (°C)	(∆L/L)	(∆L/L) %
0	0	0
-100	-0.001	-0.1
-200	-0.002	-0.2
-500	-0.005	-0.5
-1000	-0.01	-1
-2000	-0.02	-2
-3000	-0.03	-3
-4000	-0.04	-4

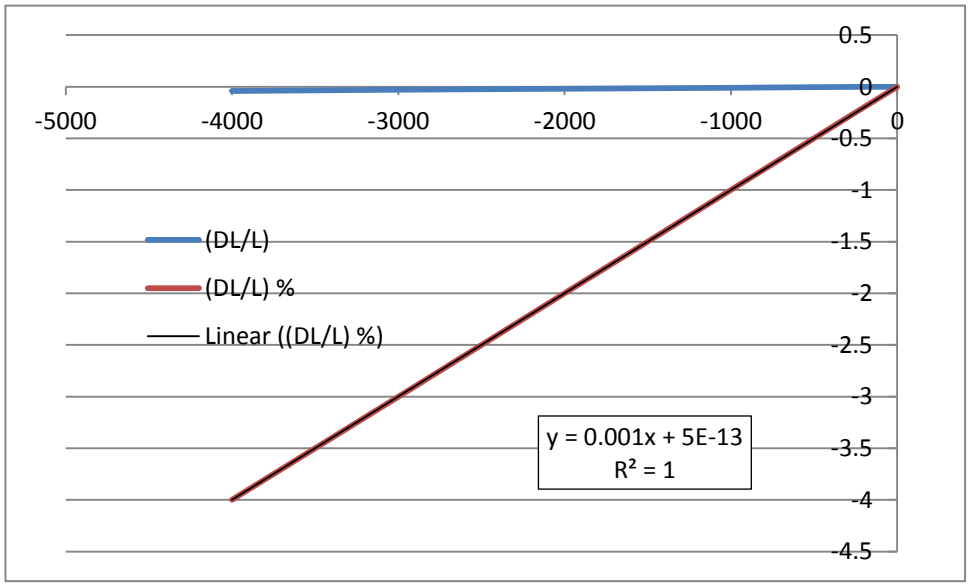


Figure 9.2: Plot of the data from Table 20 to determine line of best fit

The line of best fit for this data, as expected is linear, and is given by Eq. (9.1).

$$\left(\frac{\Delta L}{L}\right)\% = 0.001T \tag{9.1}$$

Using equation (9.1) and the required shrinkage value of, $\left(\frac{\Delta L}{L}\right)\% = 3.109$, this equation can then be rearranged to determine the actual value of the temperature to be applied in order to produce this displacement.

$$-3.109 = 0.001T$$
$$\therefore T = \frac{-3.109}{0.001} = -3109\ ^{\circ}C \qquad (1)$$

9.4 Evaluating Stresses Generated by Excessive Adhesive Layer Size

In most photographs for the tooth section taken of the adhesive material, it was found that the adhesive layer was as large as the Fuji layer. On account of this, the same model as shown in Figure 7.10 was analysed again, but this time, the Fuji layer was replaced with the material properties of the Optibond Solo adhesive of Table 9.3. The resulting principal stresses are given in Figures 9.3, 9.4 and 9.5.

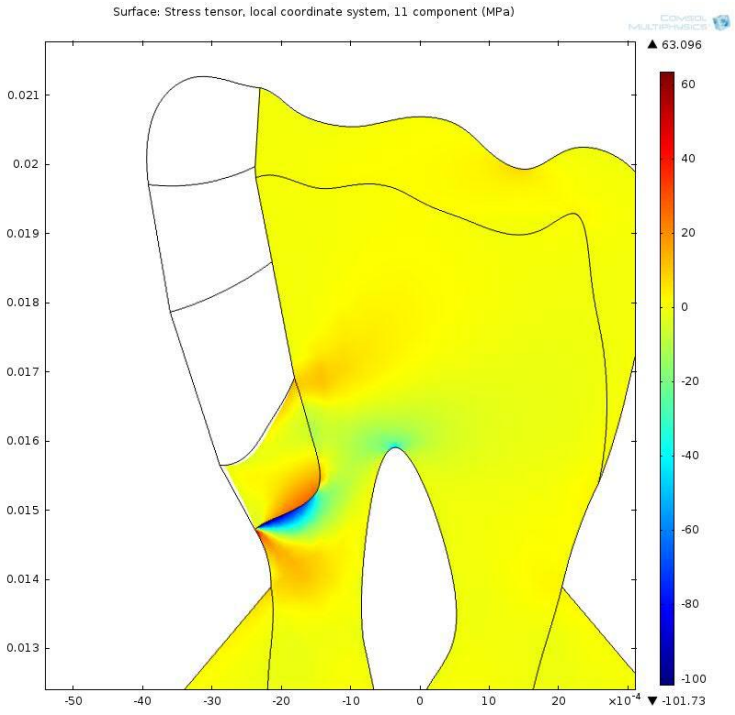


Figure 9.3: Principal stress (11), which shows the direct stresses in the structure due to the addition of the Optibond Solo Plus

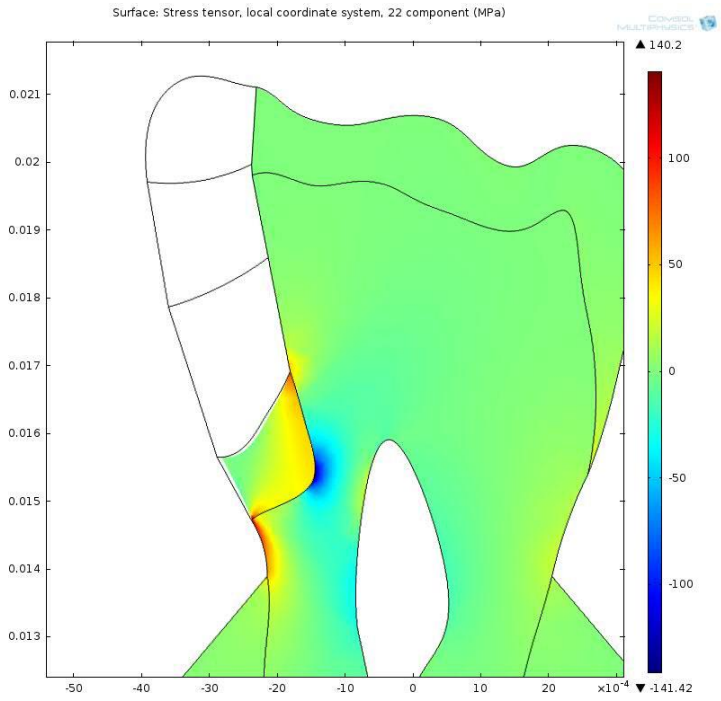


Figure 9.4: Principal stress (22), which shows the direct stresses in the structure due to the addition of the Optibond Solo Plus

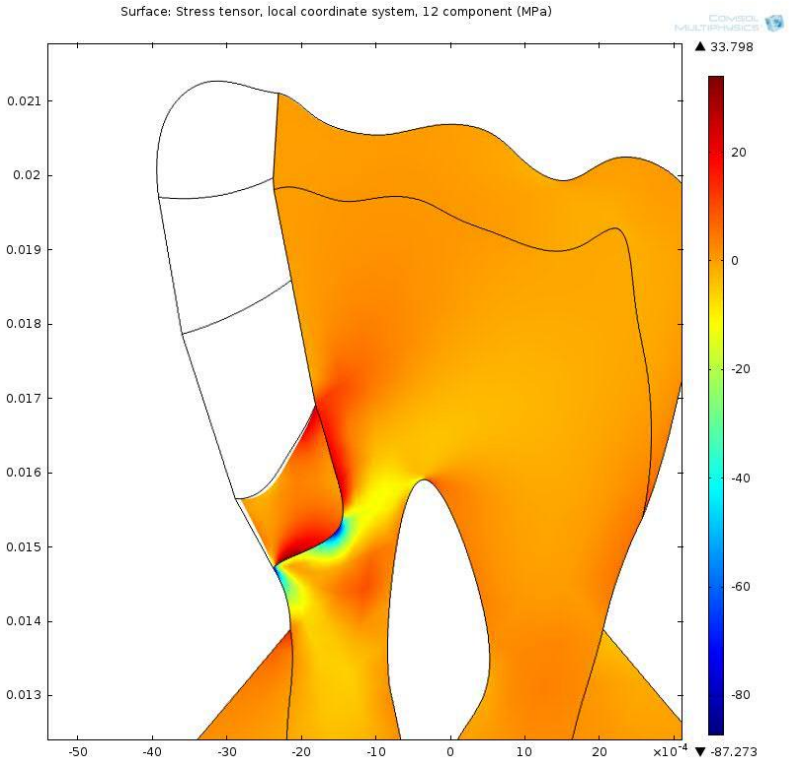


Figure 9.5: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the Optibon Solo Plus

9.5 Evaluating Stresses Generated by Adhesive Layer Size of the real Experiment

The numerical models of the section 9.4 used the size and shape of the Fuji II cement to assess the stress generated by that type of shape.

In this section, the actual adhesive layer shape of Figure 9.6 was superimposed on the model of Figure 7.10. The extra points to represent the adhesive layer were measured and are given in Table 9.5. The results of this analysis are then given in Figures 9.8, 9.9 and 9.10.

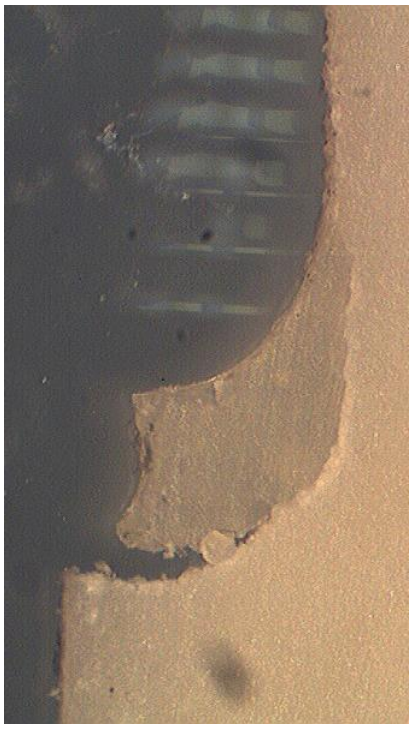


Figure 9.6: Adhesive layer thickness using Typodont tooth section (Chapter 6)

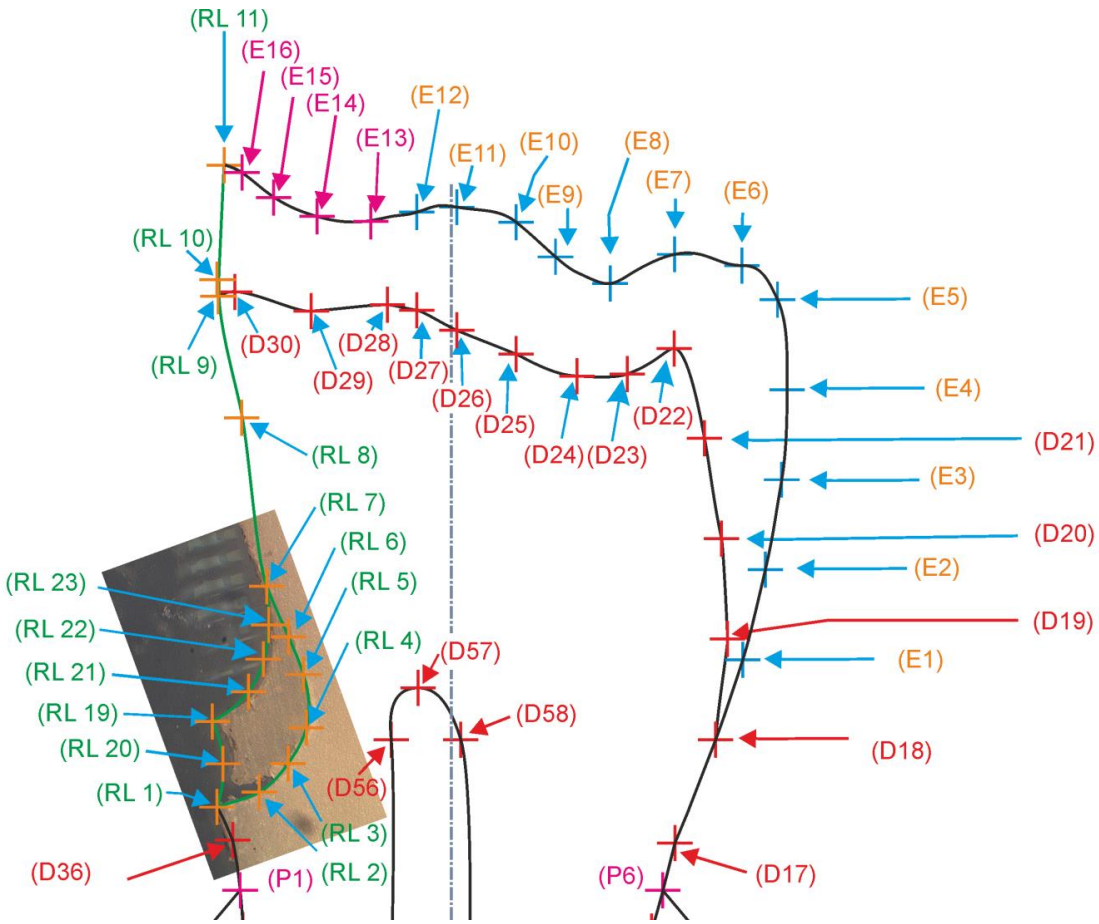


Figure 9.7: Detail of the Maxillary 2nd premolar tooth model with the adhesive layer of Figure 64 added

Table 9.5: Coordinates of Adhesive Layer		
RL1	-2.3774	14.7185
RL2	-1.9569	14.8692
RL3	-1.6705	15.1541
RL4	-1.4896	15.5061
RL5	-1.5189	16.0393
RL6	-1.6669	16.4142
RL7	-1.8101	16.9169
RL19	-2.4233	15.573
RL20	-2.3173	15.1502
RL21	-2.0642	15.8669
RL22	-1.9179	16.1915
RL23	-1.8635	16.5311

9.6 Result:

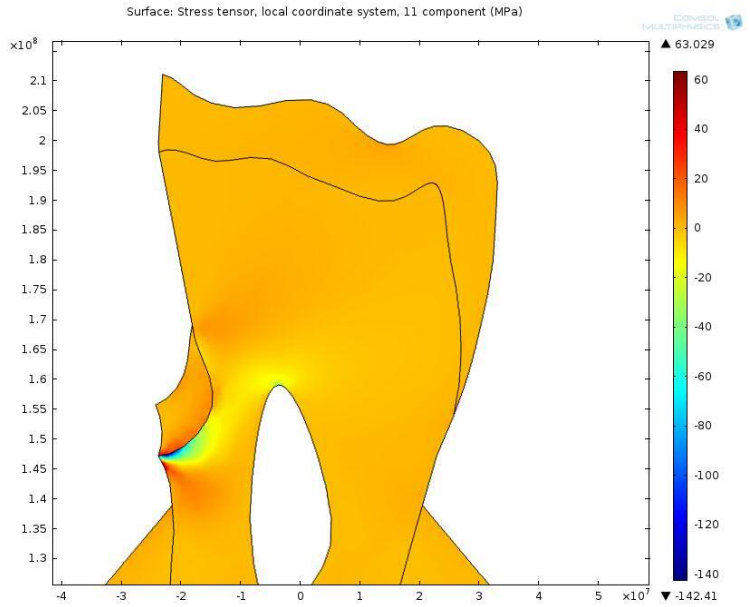


Figure 9.8: Principal stress (11), which shows the direct stresses in the structure due to the addition of the adhesive layer

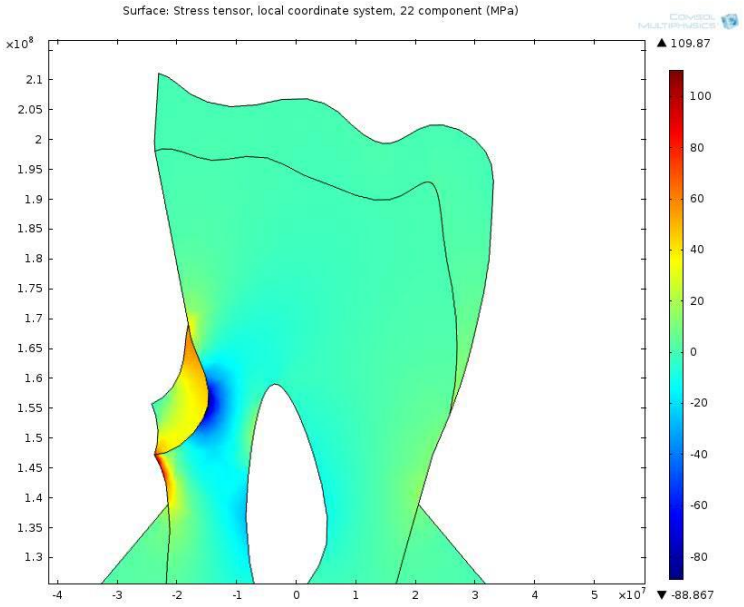


Figure 9.9: Principal stress (22), which shows the direct stresses in the structure due to the addition of the adhesive layer

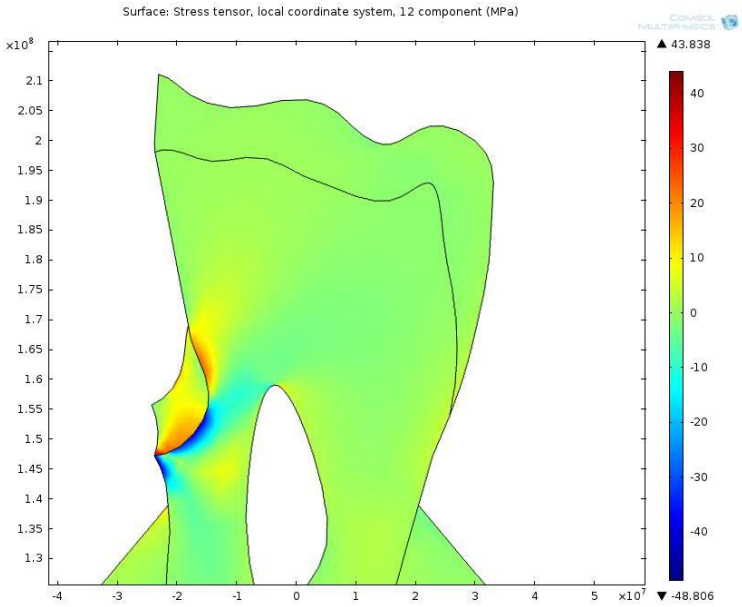


Figure 9.10: Shear stress (12), which shows the maximum shear stresses in the structure due to the addition of the adhesive layer

The result of Figures 9.8, 9.9, 9.10 shows that stresses induced by shrinkage of the adhesive layer were very high. Those regions of high stress correlate with the area of the tooth section (Figure 9.6) which shows adhesive debonding.

9.7 Discussion:

The ambivalence of much of the published research in relation to the effect of the adhesive thickness on adhesion to the tooth is problematic. Researchers have presented different findings in terms of whether using a thick adhesive layer under the restoration could provide a good seal and elastic buffer or conversely lead to an early failure of the restoration. One study Opdam et al. (1997) proposed that a thick adhesive layer could prevent gap formation between tooth and restoration and perform as an elastic buffer when compared with thin layer. Another study (Hilton and Schwartz, 1995) presented a contradictory finding, showing that a thick adhesive layer adversely effected the

longevity of the restoration by increasing crack propagation and minimizing bond strength. This finding was supported by de Menezes et al, (2013) who stated that excess adhesive may negatively affect bond strength of the adhesive material to the tooth structure. The results of the previous studies, which showed the negative effect the thick adhesive layer have on the early failure of the restoration, are consistent with the findings of the current study in which the adhesive employed (Optibond solo) has shown high volumetric shrinkage of 9.04 % and early debonding.

Grossman and Setzer, (2001) recommended that to ensure consistency of bonding and uniform stress distribution along the restoration margin, the film thickness of the adhesive material has to be even.

The difference in the results of the previous studies may be explained by the different types of materials used, the location of the restoration, type and size of the cavities, the operator skills and methodology followed in the study. It is therefore difficult to make comparisons between these research findings.

9.9 Conclusion

Use of the adhesive material in proximal restorations showed a high stress distribution so its use under RMGIC cement may lead to increased stress generated at the gingival margin and consequently lead to debonding and gap formation.

The next chapter presents two pilot studies undertaken to attempt to investigate the reasons for the adhesive pooling.

Chapter 10

Conclusion

In this final the main focus was on what has been achieved in these studies along with the conclusion and the analysis of the limitation of the studies

10.1 Achievements

The achievements of this work add to the existing scientific knowledge in the dental field in the following areas:

1. The development of a numerical tooth model for the FEA for the sandwich restoration technique
2. A qualitative linear elastic FE analysis investigated the stress distribution in a RMGIC/RC sandwich restoration.
3. A stylus model of a clinical cavity preparation was developed.
4. The findings of the laboratory study show an unexpectedly thickened adhesive layer when following the manufacturer's application instructions.
5. The thickened adhesive layer showed crack propagation into the body of the restoration.
6. This work also demonstrated that the placement of a matrix band after adhesive application does not eliminate pooling of the adhesive at the cervio-axial cavity angle.
7. Although the angulation of the tooth appeared to influence the presence of a thickened adhesive layer at some angulations, it appeared to have no influence at others.

8. This work showed that the production of a thin adhesive layer, as recommended by the manufacturer, appeared to be unpredictable and difficult to achieve when following the instructions supplied.
9. The instructions provided for the placement of the resin adhesive were open to wide interpretation by different clinicians and even where it appeared that consistent technique was used, the thickness of adhesive layer achieved was unpredictable.

10.2 Conclusions

Within the limitation of these studies, it can be concluded that:

1. The Dye penetration test failed to show a difference between the two techniques (separate curing and co-curing) due to dye absorption by the adhesive resin. It can be concluded that silver nitrate is not compatible with Optibond solo plus adhesive and not advocated for dye penetration studies using this adhesive material. The stereomicroscope examination showed no difference between the two techniques. However, the adhesive thickness varied considerably between the samples.
2. FEA of stress generated using RMGIC/RC sandwich restoration revealed that the stress was within the limits of tensile, compressive and shear stresses for the dentine, enamel, adhesive, Fuji and Herculite materials. Addition of a new layer can relieve (reduce) the magnitude of the stresses induced by the curing of a previous layer.

3. Pooling of the adhesive was still evident without the use of the matrix band.
4. The thickness of the adhesive layer was far thicker than manufacturer's recommendations which was 10 microns.
5. FEA has shown that the use of the adhesive material in proximal restoration showed a high stress distribution so its use under RMGIC cement may lead to increase stress generated at the gingival margin and potentially lead to debonding and gap formation.
6. Adhesive application is a sensitive multi-stage procedure and further work may be needed to develop a consistently thin adhesive layer.
7. Angulation of the tooth during adhesive application may have an effect on, adhesive pooling and lead to a thick adhesive layer.
8. Lack of detailed and vague instructions for adhesive application could lead to many different interpretations which could affect the accuracy and consistency of the application of the adhesive. Manufacturers should be made aware of this and seek to develop protocols for use which can be applied consistently by different operators in different working environments working with a range of dental equipment. If necessary, new equipment may need to be developed to facilitate consistent use which maximises the attributes of the material.
9. Multiple variables such as air thinning, position of the syringe and also time of air application could result in considerable differences in the adhesive thickness.

10.3 Limitations of the study

1. This study has been unable to demonstrate stress distribution using a viscoelastic model as there is currently no published data on the viscoelastic nature of the materials used in this study (Fuji II, Herculite) before and after curing. The complexity of generating this model and the limitation in available time, only allowed for a linear static analysis.

2. The use of the silver nitrate dye penetration test when using a hydrophilic adhesive such as Optibond Solo Plus was shown to be inappropriate as the dye was taken up by the resin and therefore did not allow dye penetration between the resin and the tooth to be detected.

4. From the results of the multiple operator pilot study investigating the operator compliance with the manufacturer's adhesive application instructions, there are likely to be numerous complex factors affecting the ability to achieve a thin adhesive layer and it was not possible to investigate these within this thesis.

10.4 Suggestions for future research

There are a number of areas of further research indicated by the findings of this thesis.

1. Based on the previous analysis, one area for the future research could be the identification of the viscoelastic properties of the adhesive material and its volumetric shrinkage. It would then be possible to undertake viscoelastic FE analysis for sandwich restorations to investigate the effect of a simultaneous curing protocol on stress distribution.

2. Further research is required to identify which of the many variables in adhesive placement influences the production of a thin adhesive layer.
3. Identification of an appropriate dye in order to carry out dye penetration tests using the micro CT technique without dye uptake by the adhesive.

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Appendices

Appendix A. Chapter3 Documents prepared for ethical approval for teeth collection

A.1 Patient information sheet (for children aged 12-17)

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UNIVERSITY OF LEEDS

Patient Information Sheet (For children aged 12-17)

Project Title: A study of leakage around white fillings

A poor filling can cause pain and discomfort. We are trying to find a better way to do fillings.

What is the purpose of the study?
This study, which will be done in a laboratory, is to help us find the best way to fill teeth. Extracted teeth will be used for this study.

For your information: Once a tooth is taken out, it is usually thrown away. However, these teeth can be useful for research. We would like to ask you to give your extracted tooth or teeth to us to be used in our research project.

Who is doing the study?
The study will be run by Sakina Edwebi, PhD Student at Leeds Dental Institute.

Why have I been asked to participate?
As you are going to have your tooth or teeth taken out for dental reasons, we would like to have your permission to use it for my research which is a part from a PhD project instead of throwing it away.

What happen if I change my mind?
Once the tooth has been used by us, we cannot return it to you. You will have agreed to give it to us, without getting it back.

Who funds the research?
Our study is paid for by Leeds Dental Institute.

Will I benefit directly by donating my tooth/teeth to be used in this project?
Agreeing to give us your tooth/teeth will not affect the rest of your treatment in any way. You will not benefit in any way from giving it. If you do not agree to give your tooth, your current or future treatment will not be affected in any way.

Thank you for taking time to read this sheet.

If you agree to take part, would like more information or have any questions or concerns about the study please contact:
Mrs Sakina Edwebi
PhD Student at Leeds Dental Institute
den5se@leeds.ac.uk

Version 2, 30/01/2012

Professor Paul A Brunton
PhD MSc BChD FDS RCS Rest Dent (Edin) FGDP (UK) RCS (Eng) FDS RCS (Eng)
Professor of Restorative Dentistry
Director of Student Education

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A.2 Assent form for children aged 12-17 years

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Patient identification number for this study:

ASSENT FORM FOR CHILDREN AGED 12-17y

Title: A study of leakage around white fillings

1) I have read the patient information sheet.	Yes ☐	No ☐
2) I have had the opportunity to ask questions about the way that my extracted tooth/teeth will be used for the proposed study.	Yes ☐	No ☐
3) I have had the opportunity to discuss the research that is to be carried using my extracted tooth/teeth.	Yes ☐	No ☐
4) I am satisfied with the answers to my questions.	Yes ☐	No ☐
5) I understand that I can refuse to donate my extracted tooth/teeth and that it will not affect my treatment now or in the future.	Yes ☐	No ☐
6) I agree that my tooth/teeth removed as part of my treatment can be used in the proposed research.	Yes ☐	No ☐

Signature of patient---------- Date----------

Name (block capitals)----------

Signature of witness---------- Date----------

Name (block capitals)----------

Parent signature---------- Date----------

Name (block capitals)----------

Version2, 30/01/2012

Professor Paul A Brunton
PhD MSc BChD FDS RCS Rest Dent (Edin) FGDP (UK) RCS (Eng) FDS RCS (Eng)
Professor of Restorative Dentistry
Director of Student Education

The Leeds Teaching Hospitals NHS

A.3The adult information sheet

Leeds Dental Institute

University of Leeds
Clarendon Way
Leeds LS2 9LU

T +44 (0) 113 343 6199
F +44 (0) 113 343 6165
E dentistry@leeds.ac.uk

UNIVERSITY OF LEEDS

Adult Information Sheet

Project Title: A study of leakage around white fillings

A poor join between a filling and the tooth can allow fluids, food particles, and bacteria to pass into the deeper part of the tooth. This can lead to a decayed and consequently a painful tooth.

What is the purpose of the study?
This Laboratory study will be carried out to examine leakage between a filling and the tooth surface. The study could contribute to developing better fillings. Extracted teeth are going to be used for this study.

For your information: extracted teeth are usually thrown away. However, these teeth can be a useful source of material for use in scientific research.
We would like to invite you to give your extracted tooth or teeth to be used in my research project. Please note that teeth are give as an unconditional gift.

Who is doing the study?
The study will be run by Sakina Edwebi, PhD Student at Leeds Dental Institute.

Why have I been asked to participate?
As you are going to have your teeth or tooth extracted for dental reasons, we would need your permission to use it in the research as a part of PhD project, instead of throwing it away.

What happen if I change my mind?
Please bear in mind that, once your tooth is used for the research you will not be able to change your mind as we will be unable to return your tooth to you. You will have agreed to give it as unconditional gift.

Who Funds the research?
This research is funded by Leeds Dental Institute.

Will I benefit directly by donating my tooth/teeth to be used in this project?
Giving your tooth will not affect the treatment that you are about to have or your future care in any way. You personally will get no benefit from doing so. Please note that if you choose to give your tooth/teeth, you do so as a gift to scientific research.

Thank you for taking time to read this sheet.

If you agree to take part, would like more information or have any questions or concerns about the study please contact:
Mrs Sakina Edwebi
PhD Student at Leeds Dental Institute
den5se@leeds.ac.uk

Professor Paul A Brunton
PhD MSc BChD FDS RCS Rest Dent (Edin) FGDP (UK) RCS (Eng) FDS RCS (Eng)
Director of Student Education

Miss H C Russell
Mrs E Goodison
Mrs A M Iredale BS Dip HWS Cert HSC Cert HP
Mrs C E Barnes BA (Hons)
Administrative Officers

The Leeds Teaching Hospitals NHS

A.4The adult consent form

Leeds Dental Institute

University of Leeds
Clarendon Way
Leeds LS2 9LU

T +44 (0) 113 343 6199
F +44 (0) 113 343 6165
E dentistry@leeds.ac.uk

UNIVERSITY OF LEEDS

Participant Consent Form

Title of Research Project: **A study of leakage around white fillings**

Name of Researcher: Mrs Sakina Edwebi

Initial the box if you agree with the statement to the left

1	I confirm that I have read and understand the information sheet dated..... explaining the above research project and I have had the opportunity to ask questions about the project.	☐
2	I understand that my participation is voluntary and that I have donated my tooth/teeth as an unconditional gift so I will not be able to change my mind at any time.	☐
3	I understand that my name will not be linked with the research materials, and I will not be identified or identifiable in the report or reports that result from the research.	☐
4	I agree to donate my tooth/teeth in the above research project.	☐

Name of participant (*or legal representative*)	Date	Signature

Name of person taking consent (*if different from lead researcher*)	Date	Signature

To be signed and dated in presence of the participant

Version 1, 07/09/2011

Date: _____ Name of Applicant: _____

Professor Paul A Brunton
PhD MSc BChD FDS RCS Rest Dent (Edin) FGDP (UK) RCS (Eng) FDS RCS (Eng)
Director of Student Education

Miss H C Russell
Mrs E Goodison
Mrs A M Iredale BS Dip HWS Cert HSC Cert HP
Mrs C E Barnes BA (Hons)
Administrative Officers

The Leeds Teaching Hospitals NHS

A.5 Approval letter for this research by NHS Airedale, Bradford and Leeds Research Management and Governance support team

NHS
Airedale, Bradford and Leeds

NHS Airedale, Bradford and Leeds
Research management and governance support team
Research and Innovation
Level 4
Douglas Mill, Bowling Old Lane
Bradford BD5 7JR

OurRef://RMG/Approval/approval_letter_version_3

Tuesday, 1st May 2012

Mrs Sakina Edwebi
Post-graduate Student – PhD (Restorative Dentistry)
Leeds Dental Institute
Clarendon Road
Leeds
LS2 9LU

Re: The Effect of a Simultaneous Curing Protocol on Microleakage

Ref no: 001_01_05_12_0000

Thank you for your recent submission to NHS Airedale, Bradford and Leeds research management and governance support team.

Following consideration of your submission I am pleased to confirm that research management and governance permission has been granted by NHS Bradford and Airedale for the above research to take place as described in your completed application and accompanying documentation.

Conditions of permission

You should be aware that permission is granted subject to the conditions specified below:

Document	Version	Date
Evidence of insurance or indemnity		*28 September 2011*
Investigator CV		*22 December 2011*
Other: CV-Paul Brunton		*01 February 2011*
Other: CV-Helen Craddock		
Participant Consent Form: Adult	*1*	*07 September 2011*
Participant Consent Form: Child's Assent Form	*1*	*07 September 2011*
Participant Information Sheet: Adult	*1*	*07 September 2011*
Participant Information Sheet: Children	*1*	*07 September 2011*
Protocol	*1*	*07 September 2011*
REC approval letter	*1*	*04 January 2012*

- If required you must obtain an honorary contract and Letter of Access from NHS Airedale, Bradford and Leeds prior to commencing your study

Q:\Clinical Quality & Governance\Clinical Quality\Research\MASTER_RM_&_G\Approvals\11_12\001_01_05_12_0000_Edwebi.doc

A.6 Copy from the tissue transfer agreement document which was signed by the dentists contributing extracted teeth to the study

Tissue Transfer Agreement

Between the SUPPLIER, RECIPIENT and SPONSOR (if applicable) as described below.

Agreement for the transfer of human tissues / organs for non-commercial, non-therapeutic research, when the Human Tissue Act, 2004 does not apply (eg NRES project specific approval has been obtained).

RECIPIENT: Leeds Dental Institute Oral Biology Department
RECIPIENT'S LOCAL INVESTIGATOR: Sakina Edwebi
SUPPLIER: Dental Practice
SUPPLIERS LOCAL INVESTIGATOR:
SPONSOR (if applicable): Leeds University
PROTOCOL [ref]:Version 1 07 September 2011
ETHICAL OPINION ref: 001_01_05_12_0000
STUDY: The Effect of a simultaneous Curing Protocol on Microleakage
MATERIALS: Extracted Teeth
FORM OF MATERIALS SUPPLY:
PURPOSES: research as a part of PhD
RECIPIENT'S PREMISES:

1. The relevant PROTOCOL and ETHICAL OPINION is attached to this Agreement. If there is any proposed change to the PROTOCOL or ETHICAL OPINION that would have an impact upon the use, storage or otherwise of the MATERIALS, the RECIPIENT'S LOCAL INVESTIGATOR must obtain the written consent of the SUPPLIER'S LOCAL INVESTIGATOR and the SPONSOR. A change in the type of NRES approval from project specific to research tissue bank status will require a new Tissue Transfer Agreement. All agreed changes to the PROTOCOL or ETHICAL OPINION are to be attached by both parties to their copies of this Agreement.

2. The RECIPIENT agrees to only use the MATERIALS for the PURPOSES and in accordance with the PROTOCOL and ETHICAL OPINION. The MATERIALS are only to be used and stored on the RECIPIENT'S PREMISES.

3. The SUPPLIER confirms the necessary informed consents of donors/donor's representatives have been given or ETHICAL OPINION has provided an exemption to the requirement to obtain consent.

4. The SUPPLIER will deliver the MATERIALS to the RECIPIENT on the agreed delivery date(s) in the FORM OF MATERIALS SUPPLY prescribed above. A copy of the "Tissue Sample Form" to be supplied by the SUPPLIER will be forwarded with the MATERIALS.

5. The RECIPIENT agrees to ensure that all persons involved in access or use of the MATERIALS shall be made aware of, and bound by, the terms of this Agreement.

6. The RECIPIENT agrees not to transfer or distribute any part of the MATERIALS or any extracts, replications, summaries or derivatives thereof to any third party without the prior approval of the SUPPLIER, the SPONSOR and any relevant ethics committee. The RECIPIENT will provide assurance that any such transfer or distribution is within the scope of the relevant consents. Any such transfer or distribution will be subject to a separate material transfer agreement.

7. MATERIALS cannot be used for any purpose that is commercial or therapeutic. Sponsored academic or clinical research is not for these purposes deemed to be commercial.

8. The MATERIALS are supplied without warranty as to its properties, merchantable quality or fitness for any particular purposes and without any other warranty whatsoever, expressed or implied.

9. The RECIPIENT confirms that the LOCAL INVESTIGATOR is suitably qualified and will be responsible for the proper and safe handling, storage, use and disposal of the MATERIALS.

10. As soon as the STUDY has been completed by the RECIPIENT, the RECIPIENT's LOCAL INVESTIGATOR shall inform the SUPPLIER. Used MATERIALS may be retained under the terms of this Agreement only for audit and verification purposes relating to the STUDY. Unused MATERIALS will be returned to the SUPPLIER.

11. On or before expiry of NRES project specific approval (if applicable), unused MATERIALS taken from a diagnostic archive will be returned to the archive. Any other unused MATERIALS and products of the STUDY that contain human cells will be returned to the SUPPLIER and stored in premises licenced by the Human Tissue Authority. The

SUPPLIER's LOCAL INVESTIGATOR agrees to inform the DESIGNATED INDIVIDUAL for research should this situation arise, and to follow all relevant policies and standard operating procedures on the instruction of the Designated Individual.

12. Subject to the SUPPLIER meeting its commitments under this Agreement, the RECIPIENT agrees to hold harmless the SUPPLIER from any and all claims, suits and liabilities arising from any use by the RECIPIENT of the MATERIALS.

13. This Agreement may be terminated by a party upon written notice if the other party shall be in material breach of its commitments and not remedied such commitments following thirty days' written notice of the breach upon termination. Upon request the RECIPIENT shall on termination securely and confidentially either dispose of or return the MATERIALS as directed by the SUPPLIER .

14. MATERIALS shall be returned to the SUPPLIER or securely and confidentially destroyed where required for ethical reasons by the relevant ethics committee or if the donor withdraws consent.

15. This Agreement represents the entire understanding of the parties relating to the use of the MATERIALS and supersedes and overrides all other understandings. Variations require the written consent of both parties nominated representatives.

16. All communications between the parties relating to the substance of this Agreement shall take place through the RECIPIENTS LOCAL INVESTIGATOR and the SUPPLIER'S LOCAL INVESTIGATOR.

17. This Agreement shall be interpreted in accordance with English Law and be subject to the jurisdiction of the English Courts.

No third party may rely upon the provisions of this Agreement

Authorised by the HEAD OF DEPARTMENT holding the tissues (essential for tissues from LTHT diagnostic archives)	Authorised by the RECIPIENT'S LOCAL INVESTIGATOR
Department:	Designation:
Signature:	Signature:
Name:	Name:
Date:	Date:

Signed for and on behalf of the SUPPLIER	Signed for and on behalf of the RECIPIENT
Signature:	Signature:
Name:	Name:
Designation:	Designation:
Date:	Date:

Signed for and on behalf of the SPONSOR (only if applicable and the SPONSOR is not the SUPPLIER)
Signature:
Name:
Date:

Appendix B: Tables for Chapter 7

B.1: Enamel and dentine thickness at different areas Shillingburg and Grace (1973)

Table B.1: Enamel and dentine thickness at different areas

Maxillary second premolar (page 41)		Mesial (mm)	Distal (mm)
Thickness of the Enamel at 1mm from the cervical area		0.21	0.23
Thickness of dentine at 1mm from the cervical area		1.96	2.00
Average thickness of enamel (occlusal thickness)		1.55	
Average thickness of dentin (occlusal thickness)		3.27	
Enamel thickness at 4 different points from the cervical toward the occlusal (at 1mm interval) Page 41	2	0.50	0.56
	3	0.81	0.87
	4	1.10	1.10
	5	1.27	1.21
Dentine thickness 2mm above the cervical area	2	x	x
Thickness of dentin in the root area at 4 point (in 3mm intervals between each point).	cervical	1.95	1.93
	3	1.53	1.66
	6	1.21	1.39
	9	1.03	1.06

B2: Coordinates for the maxillary 2nd premolar of Figure (7.10)

Table B.2: Coordinates for the maxillary 2nd premolar of Figure (7.10)

	Number	x_{True} (mm)	y_{True} (mm)
	Reference Point (D1)	0	0
Dentine	D1	0	0
	D2	0.3634	0.9409
	D3	0.5417	1.8376
	D4	0.6158	2.7342
	D5	0.6694	3.6309
	D6	0.6369	4.5069
	D7	0.6264	5.4065
	D8	0.6263	6.2849
	D9	0.5734	7.1633
	D10	0.6475	8.1052
	D11	0.8486	8.9942
	D12	0.965	9.9233
	D13	1.2296	10.804
	D14	1.4836	11.7141
	D15	1.6847	12.6137
	D16	1.9387	13.4816
	D17	2.1715	14.3608
	D18	2.5755	15.3912
	D19	2.6952	16.3912
	D20	2.6355	17.3912
	D21	2.4663	18.3912
	D22	2.1637	19.2852
	D23	1.6997	19.0312
	D24	1.1993	19.01
	D25	0.5939	19.2281
	D26	0.0068	19.4651
	D27	-0.3932	19.6662
	D28	-0.6841	19.7191
	D29	-1.4404	19.6556
	D30	-2.2009	19.8461
	D36	-2.2226	14.3912
	D37	-2.1173	13.4945
	D38	-2.1868	12.5978
	D39	-2.1888	11.7011
	D40	-2.1522	10.8045
	D41	-2.1156	9.9078

	D42	-2.1465	9.0111
	D43	-2.1774	8.1144
	D44	-2.1571	7.2268
	D45	-2.0512	6.2849
	D46	-1.9184	5.4243
	D47	-1.6976	4.5276
	D48	-1.6022	3.6309
	D49	-1.3845	2.7342
	D50	-1.1728	1.8376
	D51	-0.9669	0.9409
	D52	-0.359	0.1341
	D53	-1.0606	6.3912
	D54	-0.924	9.4016
	D55	-0.6677	12.3912
	D56	-0.6464	15.3912
	D57	-0.379	15.9051
	D58	0.0444	15.3912
	D59	0.0655	12.3491
	D60	-0.3631	9.3912
	D61	-0.4372	6.3536
Enamel	E1	2.8468	16.1846
	E2	3.0705	17.0813
	E3	3.2334	17.978
	E4	3.2869	18.8747
	E5	3.1915	19.7714
	E6	2.839	20.1107
	E7	2.1694	20.2219
	E8	1.5281	19.9317
	E9	0.9858	20.1966
	E10	0.5939	20.5431
	E11	0.0068	20.6917
	E12	-0.3932	20.6417
	E13	-0.8506	20.5517
	E14	-1.3815	20.5995
	E15	-1.8135	20.7888
	E16	-2.1299	21.0362
Plaster	P1	-2.147	13.8912
	P2	-10.5487	3.8912
	P3	-10.5432	-3.1027
	P4	10.4513	-3.1088
	P5	10.4513	3.8912
	P6	2.0497	13.8912
Restoration (Left) co-curing	RL1	-2.3774	14.7185
	RL2	-1.6924	15.0755
	RL3	-1.4783	15.2989
	RL4	-1.4548	15.6556

	RL5	-1.5361	15.9796
	RL6	-1.6583	16.4194
	RL7	-1.8101	16.9169
	RL8	-2.1318	18.5959
	RL9	-2.367	19.8052
	RL10	-2.3771	19.9696
	RL11	-2.3067	21.1097
	RL12	-2.7688	21.2144
	RL13	-3.2619	21.2594
	RL14	-3.6647	21.0147
	RL15	-3.9117	20.4532
	RL16	-3.9373	19.9599
	RL17	-3.9155	19.7092
	RL18	-3.6013	17.8636
	RL19	-2.887	15.6553
	RL20	-2.7323	15.6607
	RL21	-2.5249	15.7696
	RL22	-2.2129	16.1871
	RL23	-1.9376	16.6456
	RL24	-2.8274	18.167
	RL25	-3.2082	19.7156

Appendix C: Chapter 5 Table and Figures

C.1: Sample randomization

Table D.1: Sample randomization

Sample Randomization	Separate curing	Co-curing
0	1M	1D
1	2D	2M
1	3D	3M
1	4D	4M
0	5M	5D
1	6D	6M
1	7D	7M
0	8M	8D
0	9M	9D
0	10M	10D
0	11M	11D
1	12D	12M
1	13D	13M
1	14D	14M
0	15M	15D
1	16D	16M
0	17M	17D
0	18M	18D
0	19M	19D
1	20D	20M
0	21M	21D
0	22M	22D
0	23M	23D
1	24D	24M
0	25M	25D
1	26D	26M
1	27D	27M
1	28D	28M
0	29M	29D
1	30D	30M
1	31D	31M

1	32D	32M
1	33D	33M
0	34M	34D
1	35D	35M
1	36D	36M
0	37M	37D
1	38D	38M
1	39D	39M
0	40M	40D
1	41D	41M
1	42D	42M
0	43M	43D
1	44D	44M
1	45D	45M
0	46M	46D
0	47M	47D
0	48M	48D
0	49M	49D
0	50M	50D
0	51M	51D
0	52M	52D
0 = start with the separate curing 1 = start with co-curing		

Appendix C.2: Chapter 5. SEM images showing adhesive thickness and crack propagation

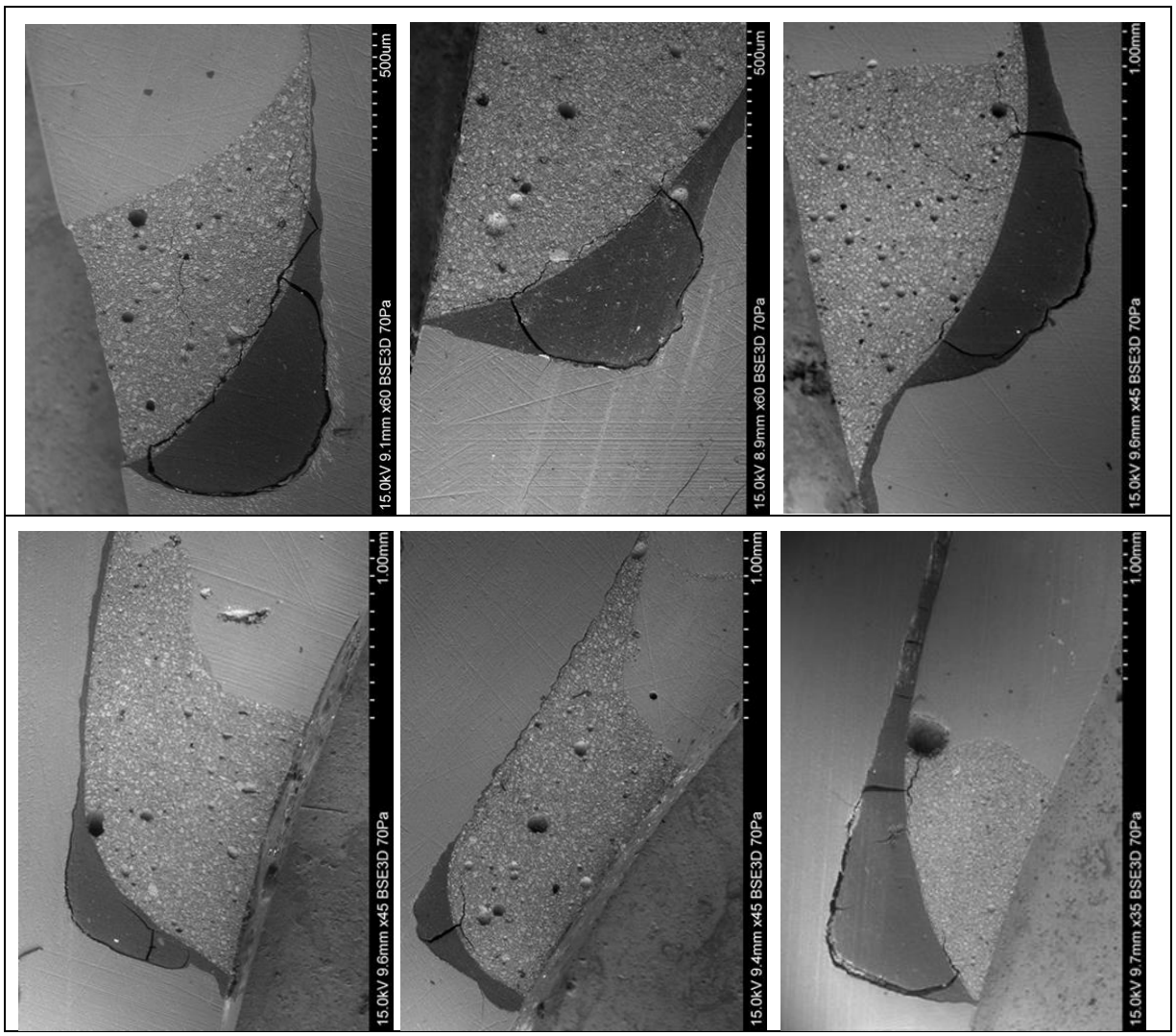


Figure C.1:SEM images showing intact margin and crack propagation in the adhesive

Appendix D: Measurement of adhesive area on Typodont teeth sections photographs from the experimental work in chapter 9 which used in chapter 8

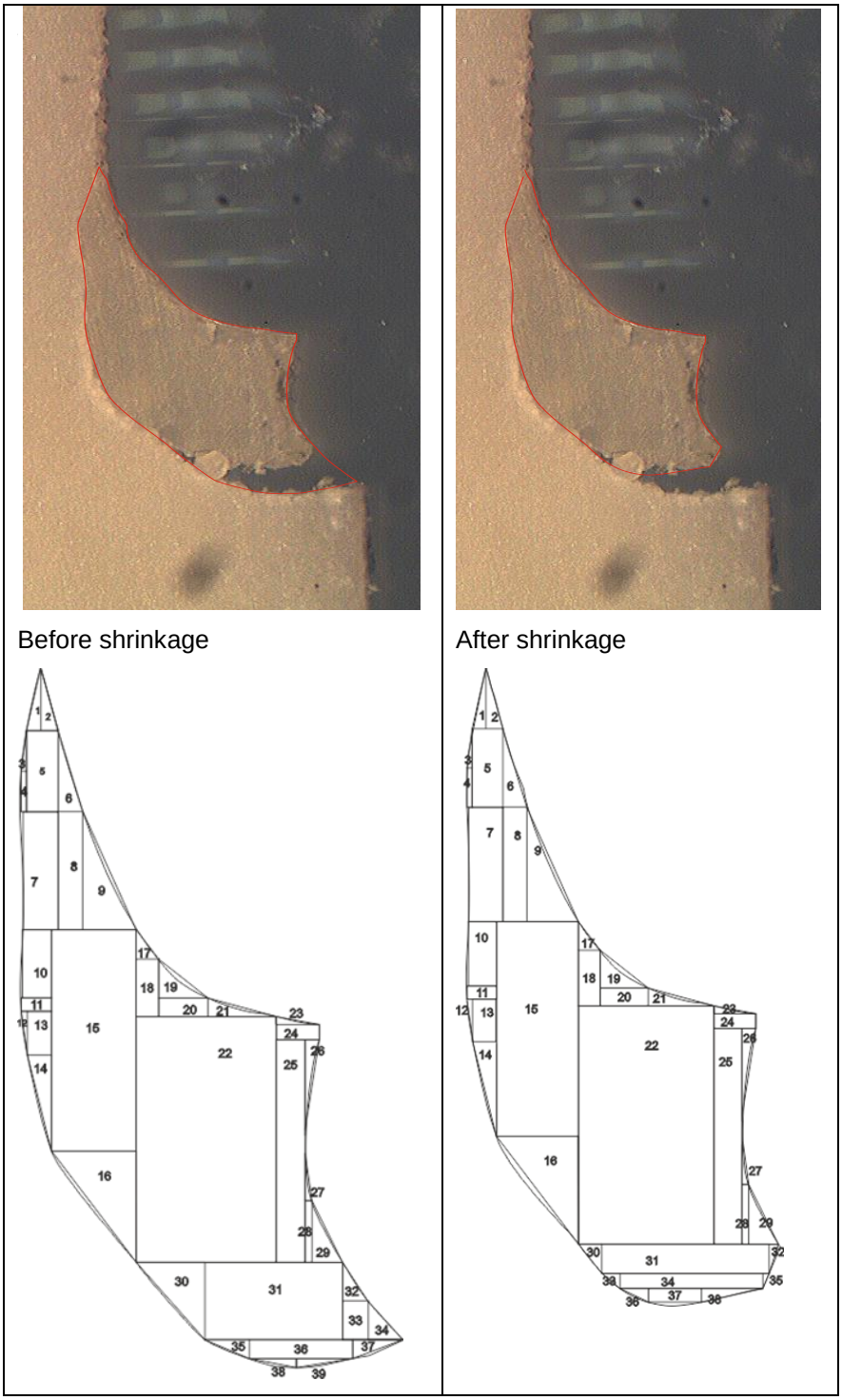


Figure D.1: Measuring adhesive area before and after adhesive shrinkage tooth section sample (number 13-90º)

Table D.1: Measurment of the adhesive area before and after shrinkage using CorelDraw(Tooth-13-90º)

Area before shrinkage			
triangle	height	width	area
1	14.933	3.244	24.22133
2	14.933	4.005	29.90333
3	9.257	1.233	5.706941
6	18.526	5.463	50.60377
9	26.954	12.162	163.9073
12	1.425	10.015	7.135688
14	5.531	21.897	60.55615
16	25.386	19.308	245.0764
17	6.727	5.174	17.40275
19	8.89	11.297	50.21517
21	15.529	4.219	32.75843
23	1.829	9.796	8.958442
26	21.902	3.262	35.72216
27	10.687	1.579	8.437387
29	7.004	14.097	49.36769
30	17.635	15.718	138.5935
32	8.817	5.864	25.85144
34	8.817	7.877	34.72575
35	10.134	4.322	21.89957
37	11.475	4.322	24.79748
38	2.061	10.773	11.10158
39	12.846	2.061	13.2378
sum			1060.18
rectangle	length	height	area
4	9.296	1.233	11.46197
5	18.526	7.249	134.295
7	8.038	26.91	216.3026
8	5.643	26.954	152.1014
10	6.667	15.551	103.6785
11	6.956	3.086	21.46622
13	5.531	10.015	55.39297
15	19.308	50.55	976.0194
18	5.174	13.109	67.82597
20	11.297	4.219	47.66204
22	31.966	56.099	1793.261
24	9.769	3.467	33.86912
25	6.59	50.804	334.7984
28	1.583	14.097	22.31555
31	31.486	17.635	555.2556
33	5.864	8.817	51.70289
36	23.618	4.322	102.077
sum			4679.485
sum of all			5739.665

Area after shrinkage			
triangle	height	width	area
1	14.933	3.244	24.22133
2	14.933	4.005	29.90333
3	9.257	1.233	5.706941
6	18.526	5.463	50.60377
9	26.954	12.162	163.9073
12	1.425	10.015	7.135688
14	5.531	21.897	60.55615
16	25.386	19.308	245.0764
17	6.727	5.174	17.40275
19	8.89	11.297	50.21517
21	15.529	4.219	32.75843
23	1.829	9.796	8.958442
26	21.902	3.262	35.72216
27	10.687	1.579	8.437387
29	7.004	14.097	49.36769
30	6.902	5.487	18.93564
32	6.902	2.182	7.530082
33	3.555	4.143	7.364183
35	3.555	1.498	2.662695
36	3.211	6.747	10.83231
38	3.211	14.464	23.22195
sum			860.5198
rectangle	length	height	area
4	9.296	1.233	11.46197
5	18.526	7.249	134.295
7	8.038	26.91	216.3026
8	5.643	26.954	152.1014
10	6.667	15.551	103.6785
11	6.956	3.086	21.46622
13	5.531	10.015	55.39297
15	19.308	50.55	976.0194
18	5.174	13.109	67.82597
20	11.297	4.219	47.66204
22	31.966	56.099	1793.261
24	9.769	3.467	33.86912
25	6.59	50.804	334.7984
28	1.583	14.097	22.31555
31	39.503	6.902	272.6497
34	33.705	3.555	119.8213
37	12.494	3.211	40.11823
sum			4403.039
sum of all			5263.559
change in area		0.91705	

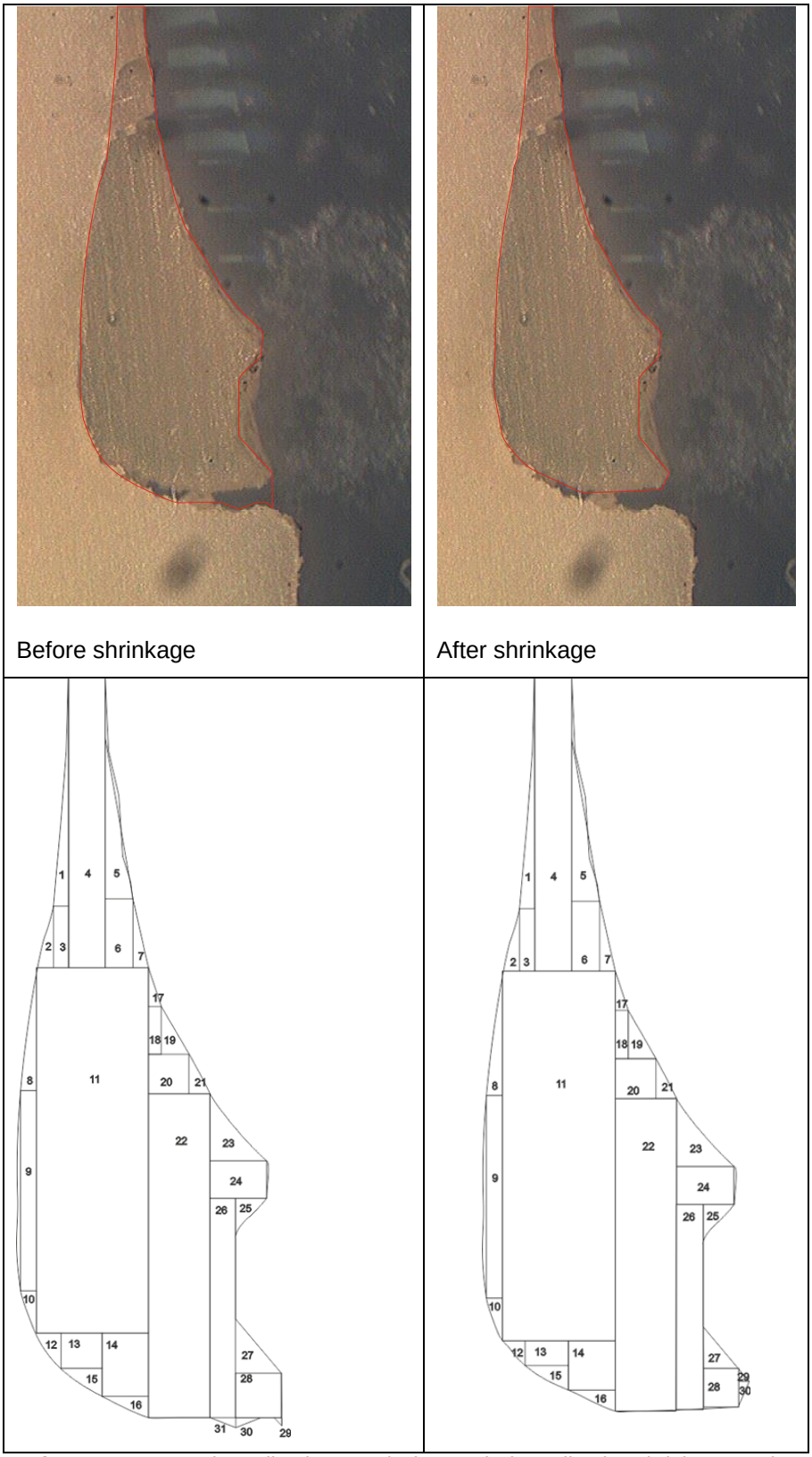


Figure D.2: Measuring adhesive area before and after adhesive shrinkage tooth section sample (number 16-105º)

Table D.2: Measurment of the adhesive area before and after shrinkage using CorelDraw tooth section sample (number 16-105º)

Area before shrinkage			
triangle	height	width	area
1	4.998	75.808	189.4442
2	20.475	5.652	57.86235
5	9.187	52.702	242.0866
7	22.88	5.159	59.01896
8	5.266	40.749	107.2921
10	5.266	14.023	36.92256
12	8.084	11.692	47.25906
15	13.64	9.344	63.72608
16	6.903	15.346	52.96672
17	12.863	4.245	27.30172
19	9.117	15.851	72.25678
21	7.011	13	45.91153
23	18.785	22.225	208.7483
25	10.315	12.396	63.93237
27	15.136	17.995	136.1862
29	2.662	2.589	3.445959
30	8.431	3.305	13.93223
31	8.431	3.305	13.93223
sum			1442.226

Area after shrinkage			
triangle	height	width	area
1	4.998	75.808	189.4442
2	20.475	5.652	57.86235
5	9.187	52.702	242.0866
7	22.88	5.159	59.01896
8	5.266	40.749	107.2921
10	5.266	14.023	36.92256
12	7.484	8.096	30.29523
15	8.066	14.174	57.16374
16	15.45	6.907	53.35658
17	12.863	4.245	27.30172
19	9.117	15.851	72.25678
21	6.711	13	42.42694
23	22.225	18.785	208.7483
25	10.015	12.066	60.4205
27	13.459	11.331	76.25196
29	3.414	4.047	6.908229
30	7.859	3.414	13.41531
sum			1341.172

Rectangle	Length	width	Area
3	4.998	20.475	102.3341
4	12.112	96.282	1166.168
6	9.187	22.88	210.1986
9	5.266	66.414	349.7361
11	37.108	121.186	4496.97
13	11.692	13.64	159.4789
14	15.346	21.035	322.8031
18	4.245	15.851	67.2875
20	13.097	13.362	175.0021
22	20.373	107.421	2188.488
24	18.785	12.435	233.5915
26	8.471	72.76	616.35
28	15.136	14.738	223.0744
sum			10311.48

Rectangle	Length	width	Area
3	4.998	20.475	102.3341
4	12.112	96.282	1166.168
6	9.187	22.88	210.1986
9	5.266	66.414	349.7361
11	37.108	121.186	4496.97
13	14.174	8.096	114.7527
14	15.45	16.162	249.7029
18	4.245	15.851	67.2875
20	13.362	13.097	175.0021
22	20.143	102.529	2065.242
24	18.785	12.435	233.5915
26	8.901	67	598.6012
28	11.567	12.647	146.2878
Sum			9975.874

sum of all area		**11753.71**

Sum of all area		**11317.05**

Change in area	0.962849

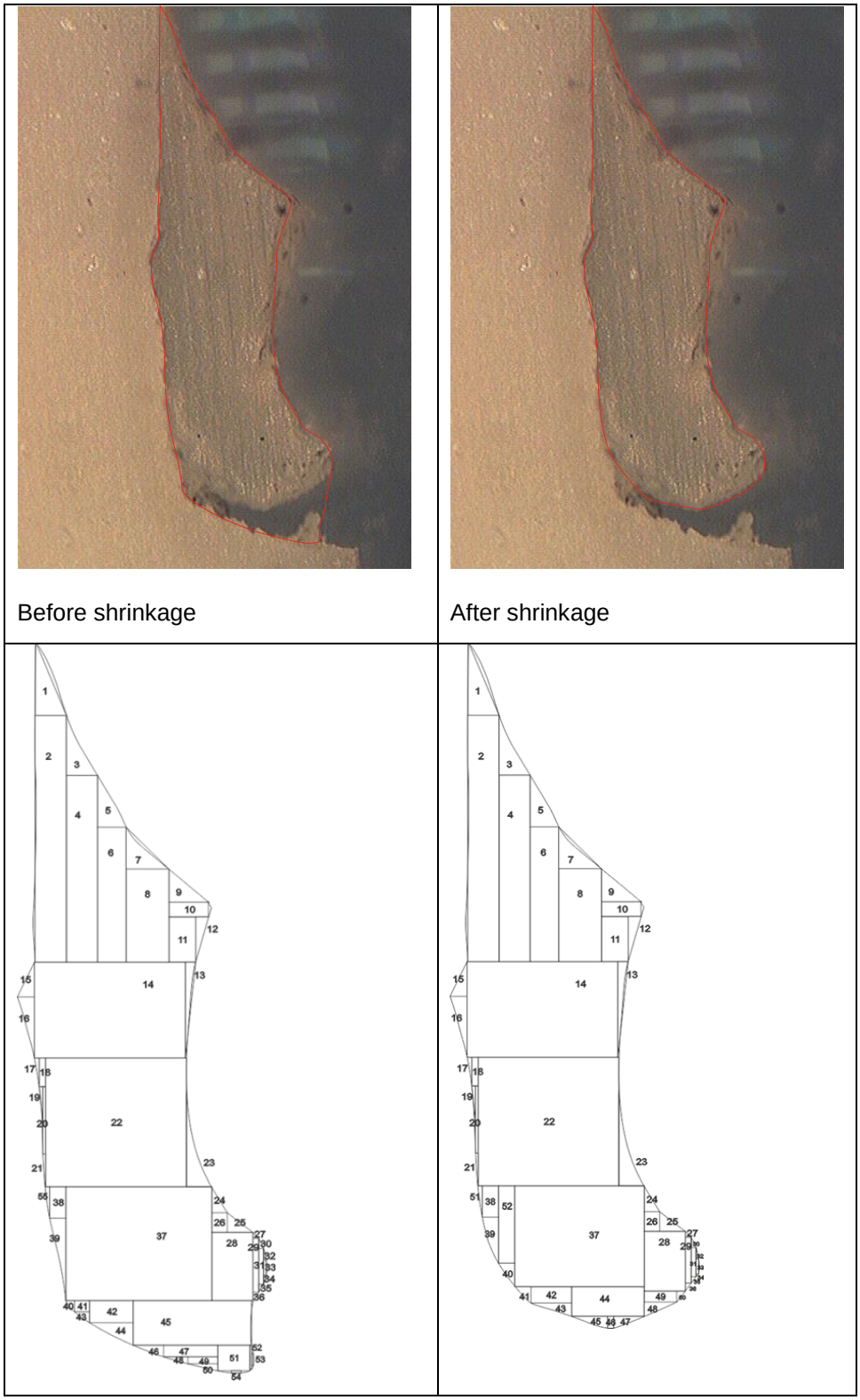
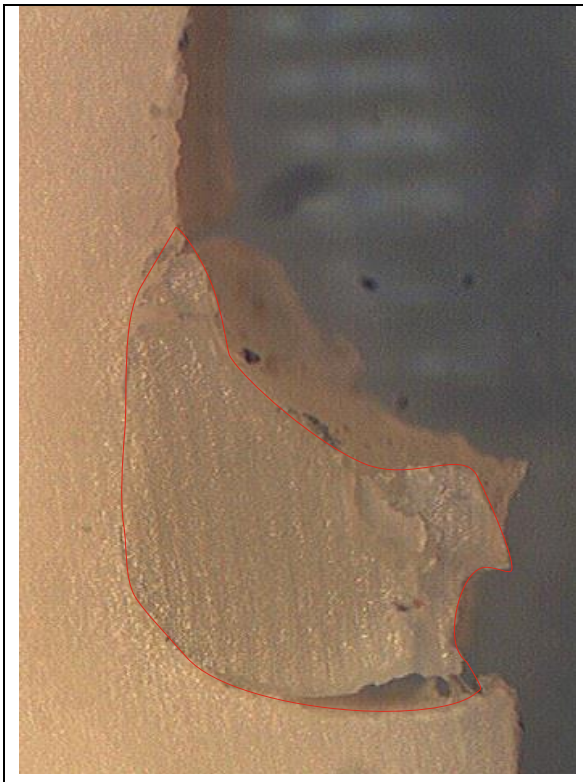


Figure D.3: Measuring adhesive area before and after adhesive shrinkage tooth section sample (number 17-120º)

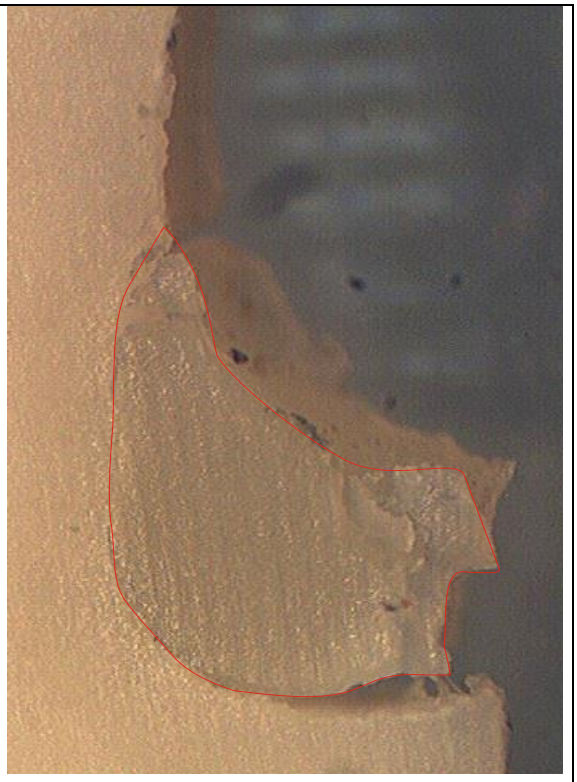
Table D.3: Measurment of the adhesive area before and after shrinkage using CorelDraw tooth section sample (number 17-120º)

Area before shrinkage			
triangle	height	width	area
1	12.056	27.993	168.7418
3	11.906	22.992	136.8714
5	10.984	19.92	109.4006
7	16.419	16.047	131.7378
9	15.092	12.624	95.2607
12	17.259	4.951	42.72465
13	4.107	36.286	74.5133
15	13.378	6.591	44.0872
16	23.405	6.591	77.13118
17	1.718	11.021	9.467039
19	12.927	1.405	9.081218
21	0.989	12.555	6.208448
23	9.791	36.446	178.4214
24	9.985	5.886	29.38586
25	7.52	9.885	37.1676
27	2.309	2.249	2.596471
30	3.925	1.841	3.612963
32	4.366	1.02	2.22666
34	3.487	1.02	1.77837
35	3.096	1.841	2.849868
36	3.211	2.249	3.61077
39	31.612	6.232	98.50299
40	3.363	4.34	7.29771
43	5.687	4.116	11.70385
44	8.688	16.808	73.01395
46	11.703	4.449	26.03332
48	9.304	2.678	12.45806
50	11.471	2.667	15.29658
55	12.086	1.782	10.76863
sum			1421.95
Rectangle	Length	width	Area
2	12.065	94.702	1142.58
4	11.906	71.702	853.684
6	10.984	51.782	568.7735
8	16.419	35.752	587.0121
10	15.092	5.649	85.25471
11	10.214	17.259	176.2834
14	57.937	36.783	2131.097
18	2.394	11.021	26.38427
20	0.989	25.854	25.56961
22	54.071	49.43	2672.73
26	5.886	7.52	44.26272
28	15.771	26.194	413.1056
29	2.249	20.674	46.49583
31	1.841	13.653	25.13517
33	1.02	3.801	3.87702
37	56.092	43.698	2451.108
38	6.232	12.086	75.31995
41	5.687	4.34	24.68158
42	16.808	8.456	142.1284
45	45.452	17.145	779.2745
47	20.775	4.449	92.42798
49	11.471	2.678	30.71934
51	12.346	9.794	120.9167
52	0.727	9.118	6.628786
53	0.625	4.669	2.918125
54	3.799	0.894	3.396306
sum			12531.76
sum of all area			13953.71
		Change in area	0.91943

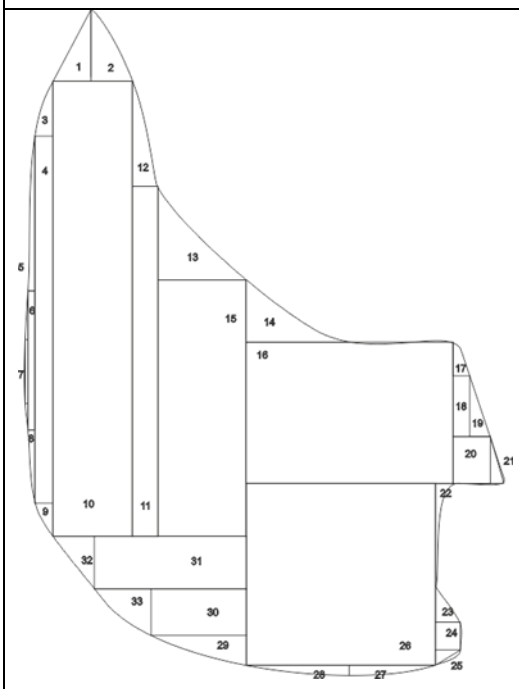
Area after shrinkage			
triangle	height	width	area
1	12.056	27.993	168.7418
3	11.906	22.992	136.8714
5	10.984	19.92	109.4006
7	16.419	16.047	131.7378
9	15.092	12.624	95.2607
12	17.259	4.951	42.72465
13	4.107	36.286	74.5133
15	13.378	6.591	44.0872
16	23.405	6.591	77.13118
17	1.718	11.021	9.467039
19	12.927	1.405	9.081218
21	0.989	12.555	6.208448
23	9.791	36.446	178.4214
24	9.985	5.886	29.38586
25	7.52	9.885	37.1676
27	2.309	2.249	2.596471
30	3.9255	1.841	3.613423
32	4.366	1.02	2.22666
34	1.073	1.02	0.54723
35	2.447	1.841	2.252464
36	3.109	2.249	3.496071
39	17.632	6.232	54.94131
40	8.886	6.25	27.76875
41	6.022	6.19	18.63809
43	5.106	15.663	39.98764
45	13.812	4.601	31.77451
47	11.686	4.601	26.88364
48	5.549	12.457	34.56195
50	3.239	4.209	6.816476
51	1.782	12.086	10.76863
sum			1417.074
Rectangle	Length	width	Area
2	12.065	94.702	1142.58
4	11.906	71.702	853.684
6	10.984	51.782	568.7735
8	16.419	35.752	587.0121
10	15.092	5.649	85.25471
11	10.214	17.259	176.2834
14	57.937	36.783	2131.097
18	2.394	11.021	26.38427
20	0.989	25.854	25.56961
22	54.071	49.43	2672.73
26	5.886	7.52	44.26272
28	15.771	22.994	362.6384
29	2.249	17.576	39.52842
31	1.841	11.204	20.62656
33	1.02	5.801	5.91702
37	49.82	38.812	1933.614
38	6.232	12.086	75.31995
42	15.663	6.19	96.95397
44	27.885	11.297	315.0168
46	2.388	4.601	10.98719
49	12.457	4.209	52.43151
52	6.25	29.717	185.7313
sum			11412.4
sum of all area			12829.47



Before shrinkage



After shrinkage



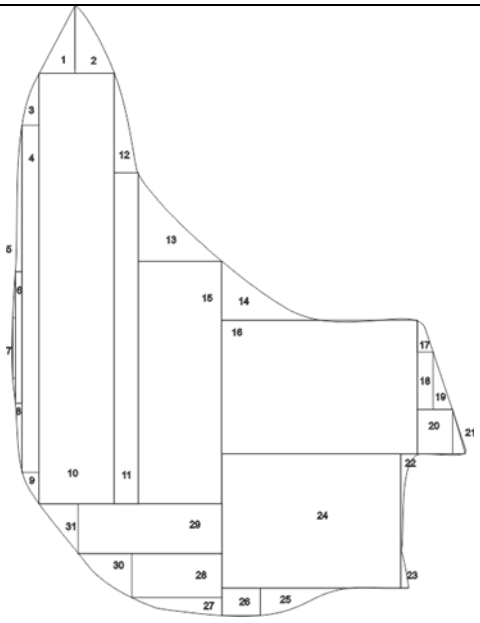


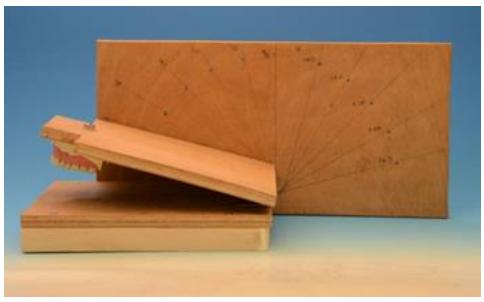
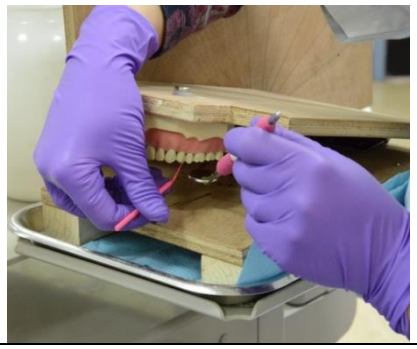
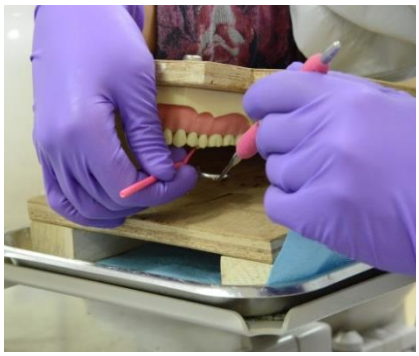
Figure D.4: Measuring adhesive area before and after adhesive shrinkage tooth section sample (number 19-135º)

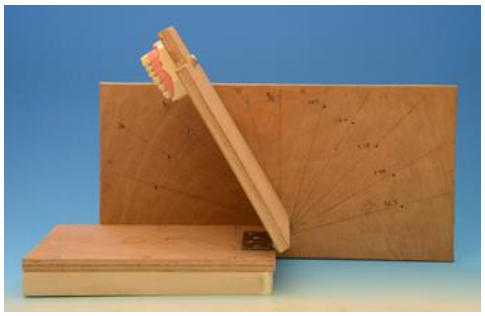
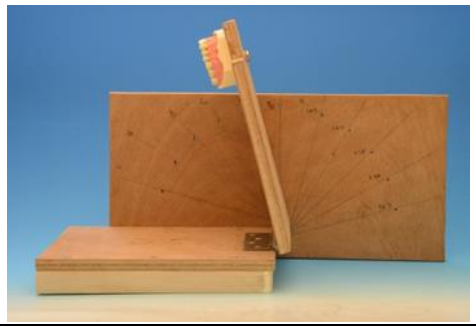
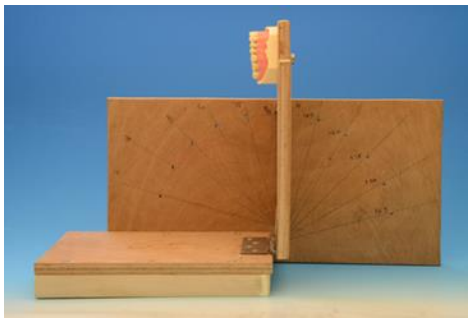
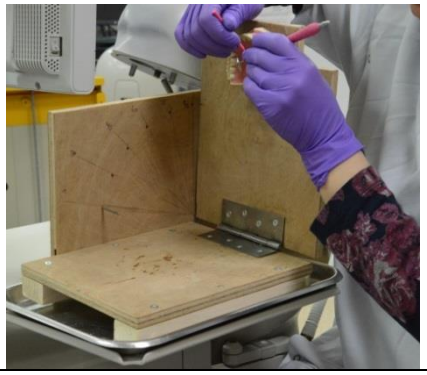
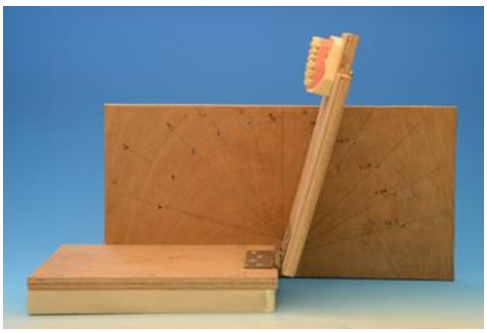
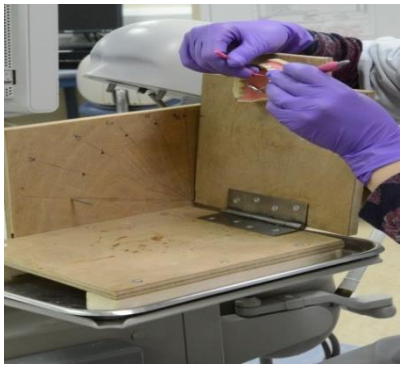
Table D.4: Measurment of the adhesive area before and after shrinkage using CorelDraw tooth section sample (number 19-135º)

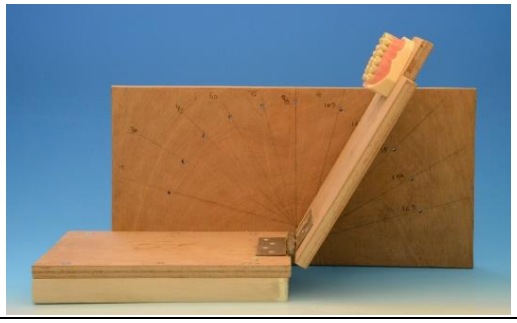
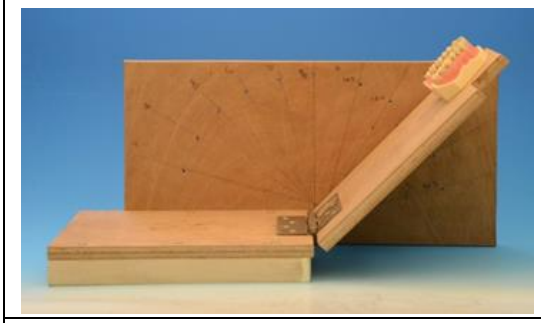
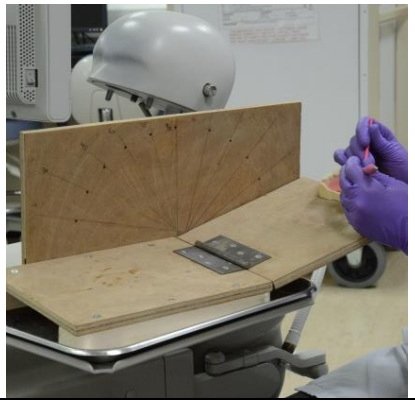
Area before shrinkage					Area after shrinkage			
triangle	height	width	area		triangle	height	width	area
1	19.744	10.568	104.3273		1	19.744	10.568	104.3273
2	19.744	11.516	113.686		2	19.744	11.516	113.686
3	15.75	4.997	39.35138		3	15.75	4.997	39.35138
5	42.896	1.917	41.11582		5	42.896	1.917	41.11582
8	20.252	1.917	19.41154		8	20.252	1.917	19.41154
9	4.997	9.21	23.01119		9	4.997	9.21	23.01119
12	29.162	7.061	102.9564		12	29.162	7.061	102.9564
13	24.442	25.947	317.0983		13	24.442	25.947	317.0983
14	28.963	17.278	250.2114		14	28.963	17.278	250.2114
17	9.308	4.663	21.7016		17	9.308	4.663	21.7016
19	5.595	16.806	47.01479		19	5.595	16.806	47.01479
21	3.738	13.031	24.35494		21	3.738	13.031	24.35494
22	28.418	5.276	74.96668		22	28.418	5.276	74.96668
23	10.033	7.753	38.89292		23	10.941	2.359	12.90491
25	4.127	6.894	14.22577		25	25.243	8.014	101.1487
27	23.623	2.83	33.42655		27	26.458	5.285	69.91527
28	28.531	2.83	40.37137		30	12.822	15.614	100.1014
29	8.334	26.458	110.2505		31	11.53	14.609	84.22089
32	11.53	14.609	84.22089		sum			1547.498
33	12.822	15.614	100.1014					
sum			1600.697					
Rectangle	Length	width	Area		Rectangle	Length	width	Area
4	4.997	101.7	508.1949		4	4.997	101.7	508.1949
6	1.617	38.552	62.33858		6	1.617	38.552	62.33858
7	0.795	17.732	14.09694		7	0.795	17.732	14.09694
10	22.085	126.16	2786.244		10	22.085	126.16	2786.244
11	7.061	97.014	685.0159		11	7.061	97.014	685.0159
15	24.442	71.022	1735.92		15	24.442	71.022	1735.92
16	57.387	39.086	2243.028		16	57.387	39.086	2243.028
18	4.663	16.801	78.34306		18	4.663	16.801	78.34306
20	10.352	13.031	134.8969		20	10.352	13.031	134.8969
24	6.894	7.753	53.44918		24	52.423	39.359	2063.317
26	52.423	50.423	2643.325		26	11.257	8.014	90.2136
30	26.458	12.822	339.2445		28	26.458	12.822	339.2445
31	42.158	14.609	615.8862		29	42.158	14.609	615.8862
sum			11899.98		sum			11356.74
sum of all area			13500.68		sum of all area			12904.24
		change in area		0.955821				

Appendix E: Figures for Chapter 6

E.1: Tooth position at different angulation during adhesive application

Angle = 15° 	
Angle = 30° 	
Angle = 45° 	

Angle = 60^{o} 	
Angle = 75^{o} 	
Angle = 90^{o} 	
Angle = 105^{o} 	

Angle = 120^{o} 	
Angle = 135^{o} 	
Angle = 150^{o} 	
Angle = 165^{o} 	

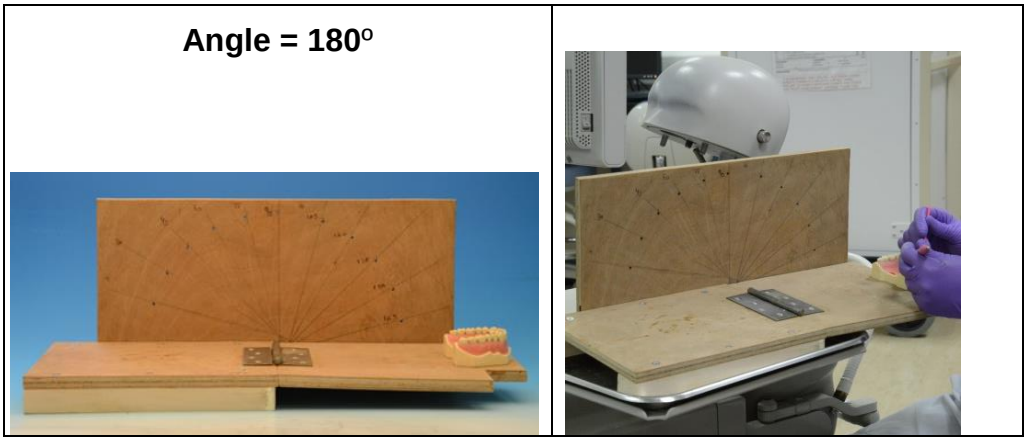
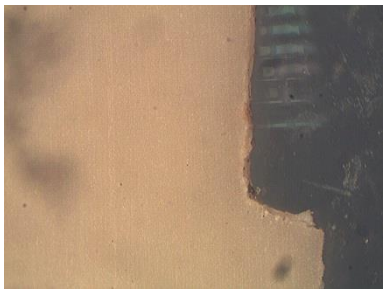
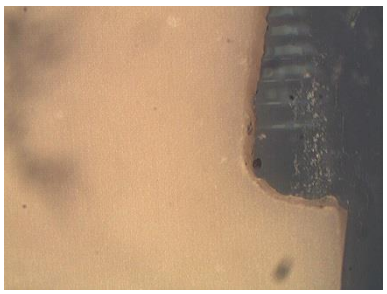
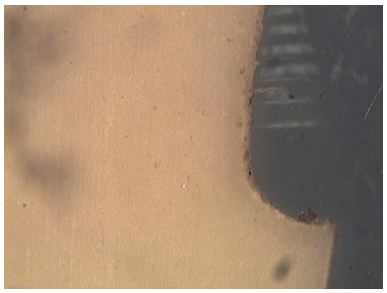
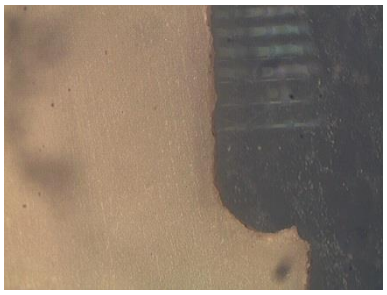
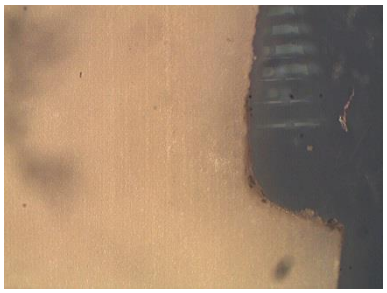
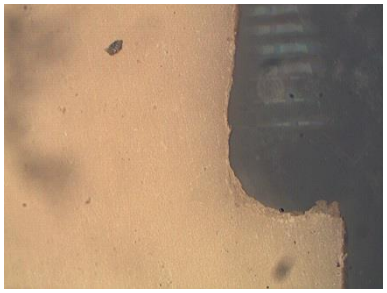
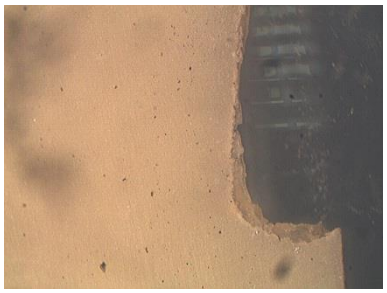
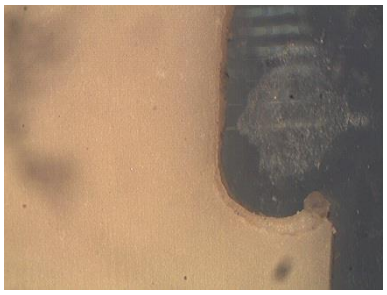
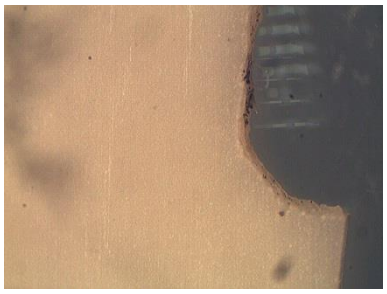
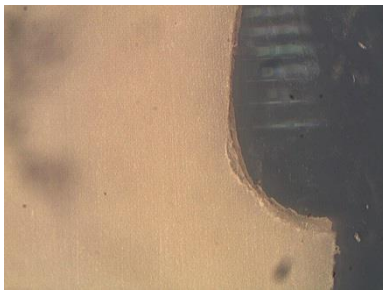


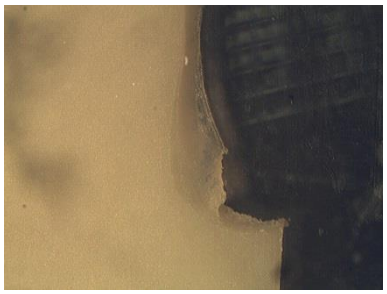
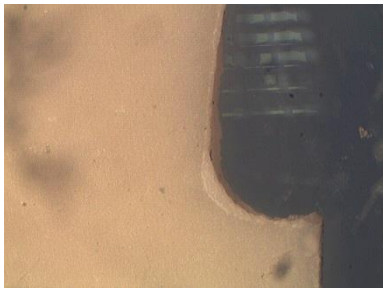
Figure E.1: Tooth position at different angulation during adhesive application

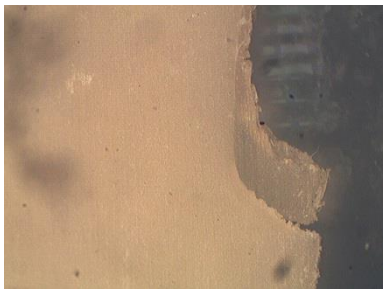
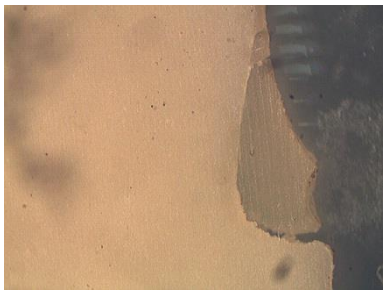
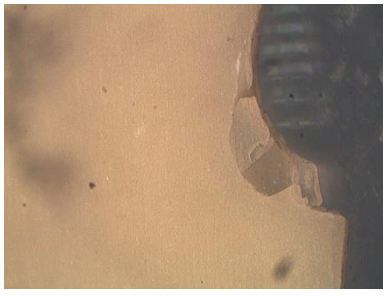
E.2: Photographs of Typodont teeth from the experimental work (Chapter 6) adhesive thickness at different angulation

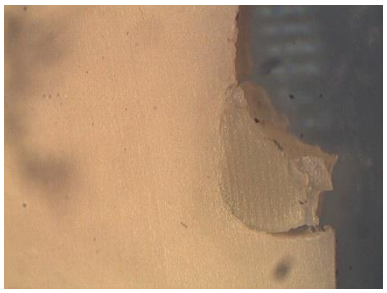
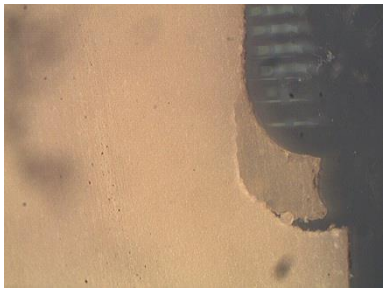
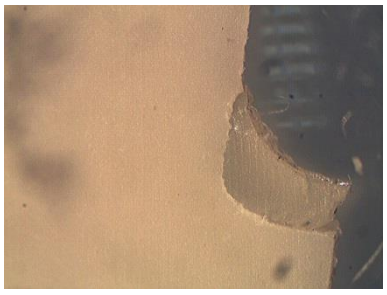
Tooth number	angle	photograph	Tooth section
1	0º		
2	0º		

3	15º		
4	15º		
5	30º		
6	30º		

7	45º		
8	45º		
9	60º		
10	60º		

11	75º		
12	75º		
13	90º		
14	90º		

15	105º		
16	105º		
17	120º		
18	120º		

19	135º		
20	135º		
21	150º		
22	150º		

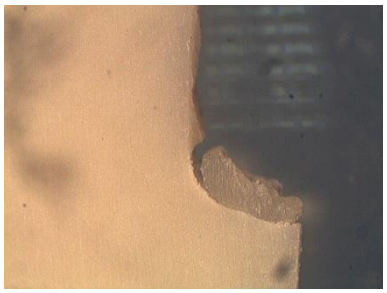
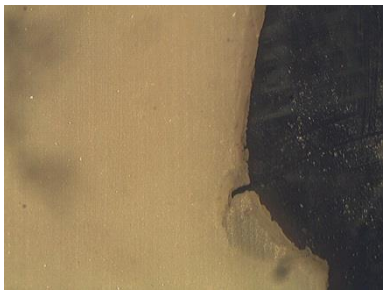
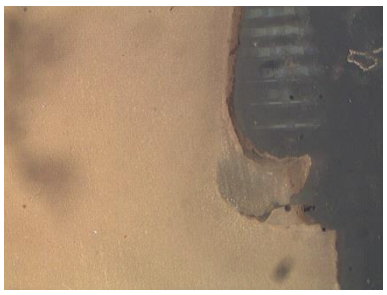
23	165º		
24	165º		
25	180º		
26	180º		

Figure E.2: Photographs for the prepared teeth before and after sectioning showing the adhesive thickness

E.3: Adhesive thickness at different angulation (main investigator)

Table E 1: Tooth position at different angulation during adhesive application

Tooth	Angle	Adhesive Thickness
1	0 º	126.3
2	0 º	121.9
3	15 º	156.7
4	15 º	152.4
5	30 º	113.2
6	30 º	113.2
7	45 º	178.5
8	45 º	187.2
9	60 º	139.3
10	60 º	139.3
11	75 º	320.8
12	75 º	483.2
13	90 º	137.5
14	90 º	143.5
15	105 º	517.6
16	105 º	653.8
17	120 º	491.4
18	120 º	395.2
19	135 º	615.2
20	135 º	588.1

21	150 º	583.4
22	150 º	577.8
23	165 º	339.4
24	165 º	335.3
25	180 º	442.3
26	180 º	291.1